Contract NAS 1-5199 Report No. 3541

RESEARCH AND DEVELOPMENT OF THE VORTEX VALVE PRINCIPLE AND ITS APPLICATION TO A HOT GAS (5500°F) SECONDARY INJECTION THRUST VECTOR CONTROL SYSTEM

Monthly Technical Report

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By

The Bendix Corporation
Research Laboratories Division
Southfield, Michigan 48076

Prepared by: W D Holt
W. D. Holt, Responsible Engineer

Approved by: J G Rivard
J. G. Rivard, Program Manager

Approved by: A. Blatter
A. Blatter, Project Supervisor

Approved by: L B Taplin
L. B. Taplin, Manager
Energy Conversion and Dynamic Controls Laboratory

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SECTION 1

INTRODUCTION

This program is the study of a vortex valve controlled secondary injection thrust vector control system, operating with highly aluminized gas from a solid propellant gas generator (SPGG). Various performance characteristics will be determined, including static and dynamic system performance and the ability of the vortex valve to handle the aluminized hot gas. The application of this technique for thrust vector control of a solid propellant rocket engine, using direct engine bleed, will be considered.

SECTION 2

SUMMARY OF RESULTS AND ACCOMPLISHMENTS

Hot gas test No. 3 of a single vortex valve was accomplished this month. The design configuration was modified from the previous test firing configuration to eliminate thermal expansion distortion and to strengthen certain sections shown by test to be underdesigned. The test system included the vortex valve, the 5500°F supply gas generator, the 2000°F control gas generator and the manual valve and manifold for control of the 2000°F gas. The test objectives were to demonstrate flow modulation with the vortex valve and to prove the new valve structural design.

2.1 5500°F VORTEX VALVE TEST NO. 3 RESULTS

The system was fired for 51 seconds. The 2000°F generator only provided control gas for 32.3 seconds under conditions for which it is designed. The control gas was admitted using a control valve operated in an on-off mode. The valve materials and structural design proved to be adequate for the duration and flow. The flow modulation realized was 1.42 to 1, which was much lower than predicted. An analysis and test program has been undertaken to determine the cause of this low performance, as discussed in detail in Section 2.2.

The cause has been attributed to erosion of the vortex valve control flow injectors early in the firing, resulting in insufficient coupling of the control flow momentum with the supply flow.

In general, the design configuration of the valve can be frozen, with the exception of the control injectors. The injectors which were made of an alloy of molybdenum will be fabricated from tungsten for the next test.

The design of the vortex button and the vortex chamber in combination with the phenolic supporting insulation appears to be good. Previous problems with collapsing of the vortex chamber liner onto the button were eliminated by providing relief grooves in the insulation. The insulation installed on the vortex button approach experienced considerable erosion, and it could possibly have affected valve performance by changing the inlet flow profile. A future modification whereby the approach flow is fed from a plenum, thus duplicating the potential future direct chamber bleed configuration, should be considered.

Another problem was that the tungsten liner in the valve outlet plenum chamber distorted during the test. A design change in the supporting insulation to allow expansion should be incorporated in the design. This outlet chamber does not contribute to vortex valve performance and only serves as a plenum for measurement of valve flow.

The gas generators performed reasonably well with essentially neutral burning characteristics. Data accumulated during the past three firings, however, does not corroborate the predicted performance supplied by Hercules and new performance criteria have been established.

Test firing No. 3 is described in detail in Appendix A of this report along with reduced data and photographs of hardware before and after firing.

The low flow modulation range required investigation to determine the cause. A series of cold gas tests were performed with a model valve. A supporting computer analysis was conducted along with these tests. The tests and analysis are described in Section 2.2.

The following are recommended vortex valve design changes before the next hot gas test:

(1) Change the control flow injector material from molybdenum to tungsten to eliminate potential erosion and resulting poor mixing of the control and supply flow.

(2) Extend the vortex button and vortex chamber leading edge to provide a better approach for the supply flow. Also consider incorporating a valve supply plenum to more nearly duplicate direct chamber bleed.

(3) Redesign the vortex valve outlet plenum to prevent distortion of the tungsten insert and to provide an accurate measurement of pressure for flow correlation.

(4) Prevent back flow of 5500°F gases through the control flow injectors at burnout of the 2000°F gas generator, which occurs before the 5500°F gas generator burnout. Possibly this can be accomplished by sequencing a control input of nitrogen to coincide with burnout to maintain a positive pressure head.

(5) Modify the control flow annulus ring by incorporating a material with higher operating temperature properties.

2.2 POST-FIRING ANALYSIS AND TEST

The lower-than-expected vortex valve flow modulation range during hot firing No. 3 was investigated by computer model simulation and test. The following are possible reasons for the low performance:

(1) The relatively cooler 2000°F control gas may not be imparting sufficient control momentum to the aluminum-oxide-rich supply gas to produce flow modulation. It is reasoned that the 2000°F control gas could be acting only on the gaseous products and not on the droplets of molten aluminum oxide. A numerical analysis comparing the momentum ratios between cold and hot gas valve performance revealed that the vortex power valve should have achieved better flow modulation on hot gas for the same equivalent control flow. The numerical analysis seems to contradict the result of the hot gas test.

(2) The vortex power valve control injectors experienced very heavy erosion at the injection end inside the vortex chamber. How and when erosion occurred cannot be supported with test data, since no abrupt change in valve performance was apparent, except during the first 2 seconds of the test. However, it seems reasonable to assume that the control injector had reached a temperature near the control gas temperature of 1950°F before the ignition of the 5500°F SPGG. It also seems reasonable to assume that, because of the available energy in the 5500°F gas, only a short time would have elapsed before the Moly-Ti injectors were heated from 1950°F to 4760°F, the melting point of molybdenum, consequently enhancing erosion. A collapsed or eroded injector would produce erroneous control flow readings, therefore invalidating the comparison of the hot gas test with the numerical analysis.

2.2.1 Testing of Particle and Erosion Effects

To determine the magnitude of each of the above on valve performance, the following tests were conducted:

Test No. 1

To determine the effect of heavy particles in the supply gas on flow modulation, lead nitrate was injected in the nitrogen supply line just upstream of a model vortex valve. Pure nitrogen was used for control flow. The lead nitrate forms droplets, which simulate the aluminum oxide particles in the 5500°F hot gas. Before the lead nitrate injection test, the model vortex valve was tested on nitrogen to establish baseline performance. A minimum flow modulation range of 5:1 was established as part of the baseline performance. A qualitative comparison could then be made between valve performance using pure nitrogen and the lead nitrate-nitrogen mixture.

Test No. 2

To determine the effect of injector erosion on valve performance, the baseline model valve was modified by removing the injectors, melting away the contoured end and replacing the injectors in the same location. Repeating the cold gas test thus would provide the necessary information for a qualitative comparison of performance between the valve with eroded injectors and the valve tested with lead nitrate solution.

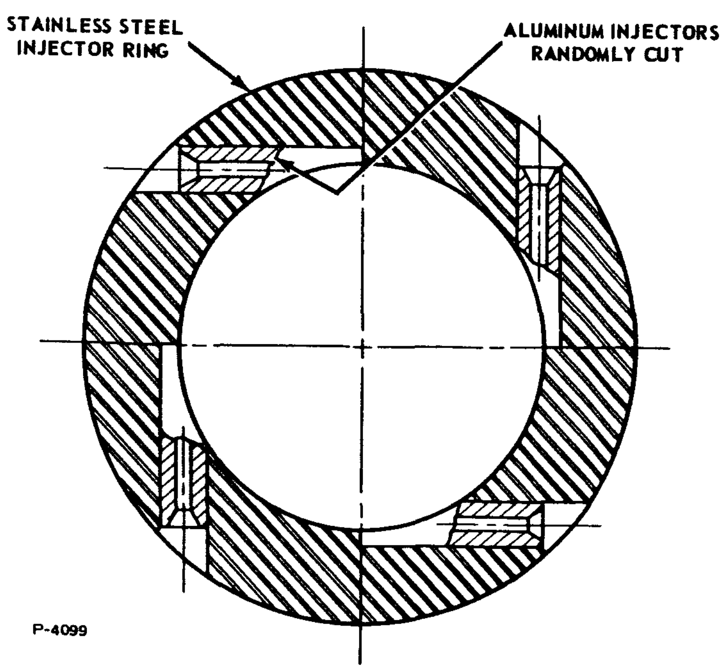


Figure 1 - Model Vortex Valve Injector Modification (P/N 2162998)

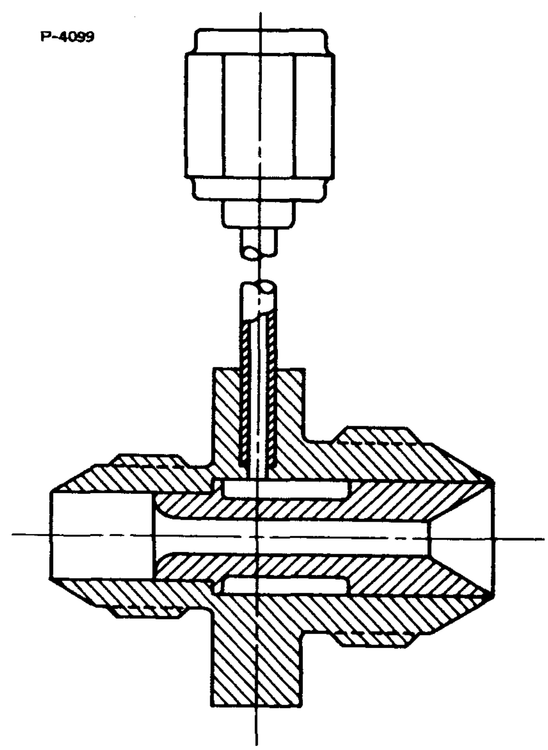


Figure 2 - Liquid Injector (P/N 2162989)

To prepare for the tests, a vortex valve utilized for another development program was modified to duplicate the 5500°F vortex valve configuration. The injectors were modified as shown in Figure 1. The injector O.D-to-I.D. ratio, as well as other critical valve dimensions, were scaled down for the model valve.

The mixing injector design for providing the liquid-gas mixture is shown in Figure 2. It is designed for a critical pressure ratio across the venturi with three equally spaced 0.020-inch diameter radial holes perpendicular with the centerline of the venturi. These are the metering holes for the injected liquid.

The tests were conducted as outlined above, using the test schematic shown in Figure 3. Results of the tests are presented and summarized in Figure 4. It is apparent that the valve, when tested with the simulated eroded injectors, showed greater performance degradation than when tested with the lead nitrate-nitrogen mixture. The tests are not completely conclusive, since the saturated solution of lead nitrate and water has a density of 0.0455 lb/in^3, compared with 0.1 lb/in^3 for aluminum oxide. This would make the volume of liquid greater in the model test but, most likely, the droplets are smaller because the viscosity is less. Assuming the droplets were the same size, their mass ratio would be 2.2 to 1. The test did present good qualitative comparison. It is deduced that the control flow inlet configuration is extremely important in achieving proper mixing of the control and supply flow. This has also been corroborated in other test programs.

2.2.2 Computer Analysis

A computer study was conducted as a parallel effort to the model vortex valve tests. This analysis was made to determine if a change in the type of control gas would produce a change in valve performance. The computer routine was derived from actual test data being accumulated on various in-house Bendix vortex valve development programs. The computer routine can simulate any basic vortex valve performance curve from nondimensionalized parameters of output flow ratio and control-to-supply pressure ratio plots and can predict (with reasonable accuracy) the valve performance with any test fluid.

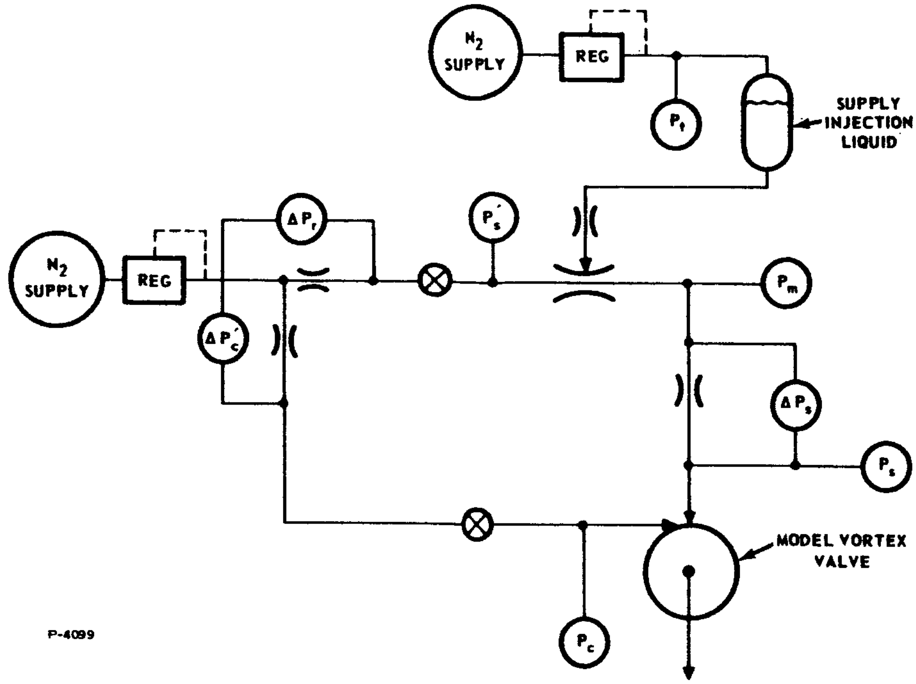


Figure 3 - Test Schematic

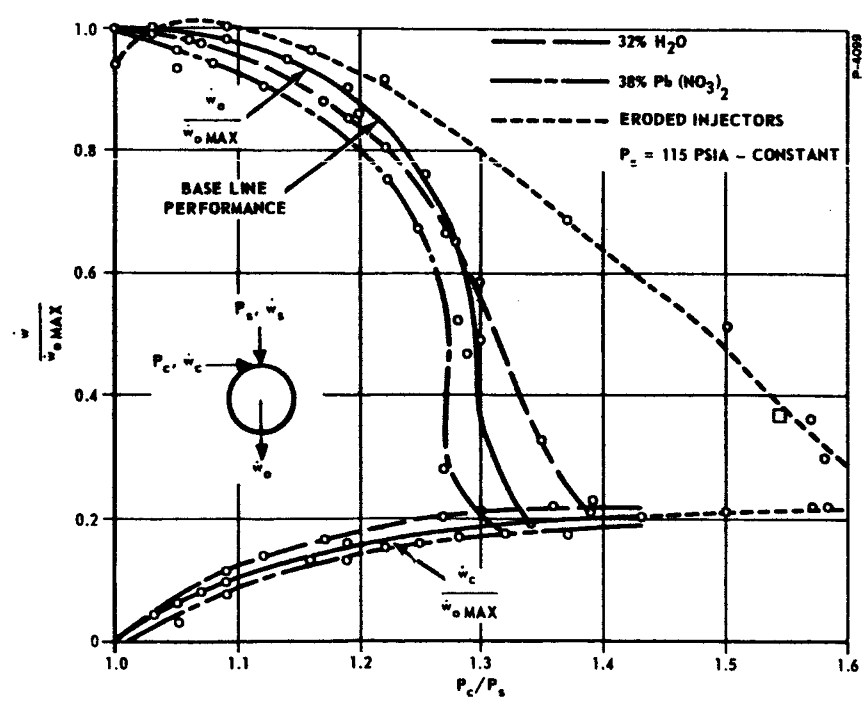


Figure 4 - Performance Characteristics of a Model Vortex Valve (P/N 2162998)

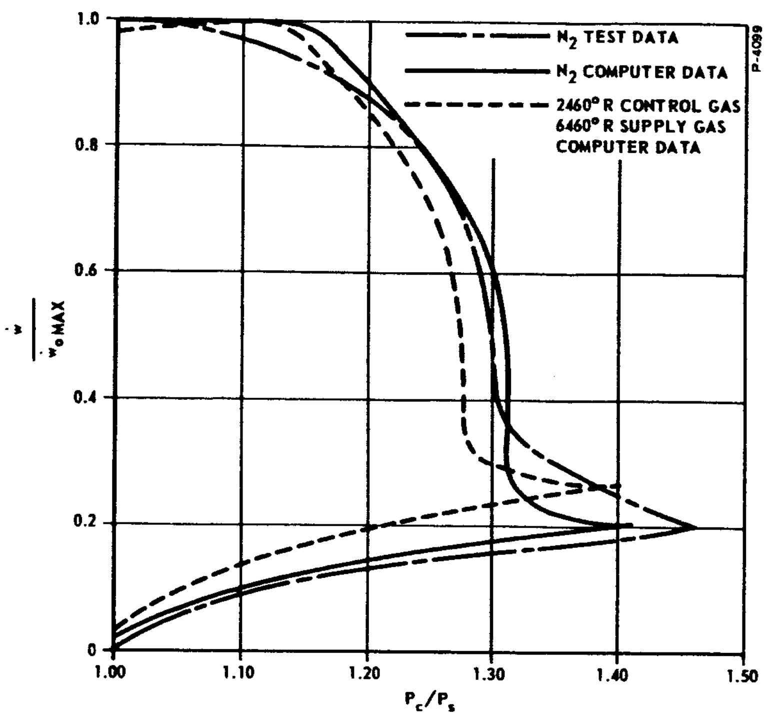


Figure 5 - Computer Study of a 5500°F Vortex Valve Baseline Analysis

The baseline performance on cold gas of the 5500°F vortex valve is shown in Figure 5 along with computed baseline performance. Superimposed on the same figure is the predicted performance using 2460°R control gas and 6460°R supply gas. The computer data indicates that the valve flow modulation will decrease from 5:1 baseline performance to 2.7:1 when 2460°F gas is controlling 6460°R supply gas.

The gas properties were changed in the computer routine for a new solution. A control gas with a temperature of 4460°R was selected. Figure 6 shows the computer results. The valve shows an improvement in flow modulation with a flow turndown of 4.55:1. In another trial solution, the control gas temperature was increased to 6460°R. The result is shown in Figure 7. The flow modulation range has increased to 5:1. The computer study is not conclusive because the aluminum oxide droplets in the supply gas were not considered. However, the computer study shows that the thermodynamic properties of the gas do influence valve flow modulation performance.

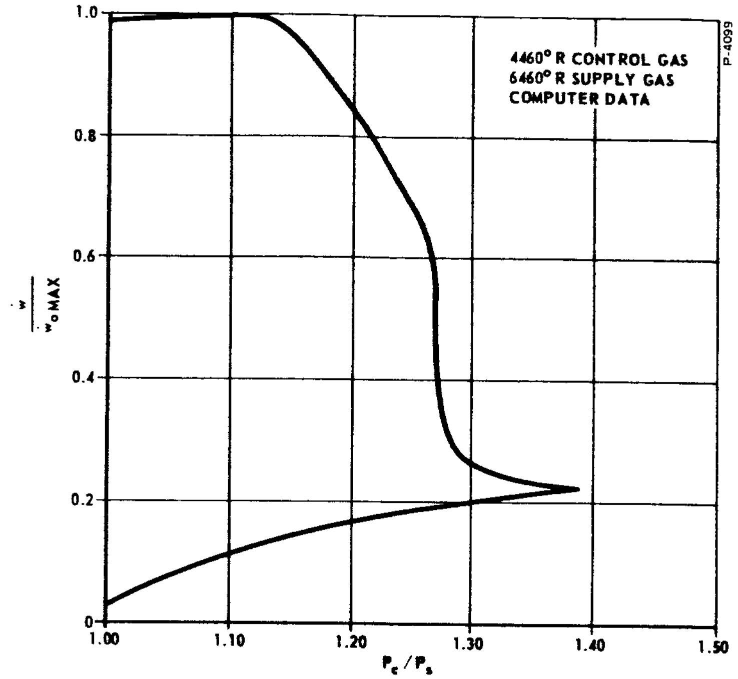


Figure 6 - Computer Study of a 5500°F Vortex Valve using 4460°R Control Gas

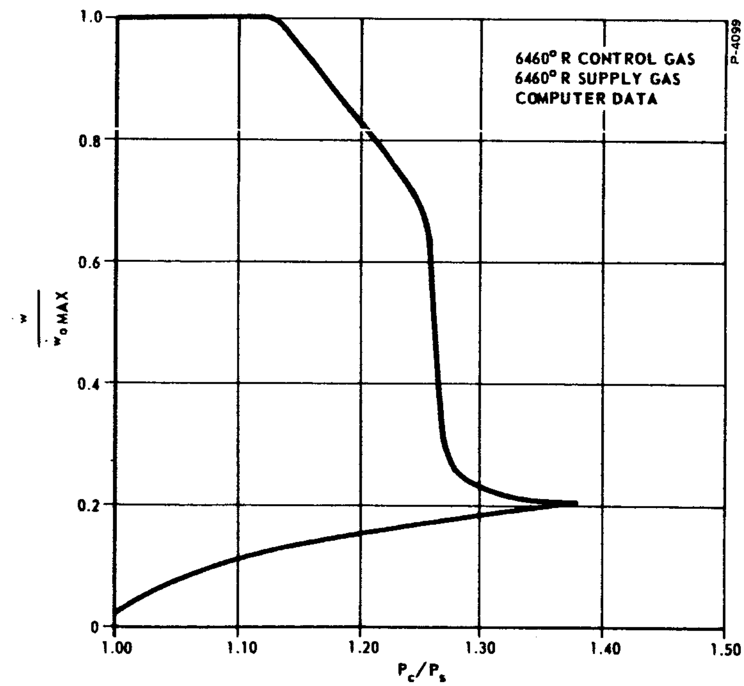


Figure 7 - Computer Study of a 5500°F Vortex Valve using 6460°R Control Gas

SECTION 3
PROBLEM AREAS

The major technical problem this period was determining which factor reduced the vortex valve flow modulation more, solid particles in the valve supply or eroded injectors. Test results on a breadboard model definitely indicated that eroded injectors influence valve performance more than the change in supply gas density. However, the actual aluminum oxide droplets in the supply gas can not be duplicated by simple means; therefore, this test was only a qualitative comparison.

SECTION 4

PLANS FOR NEXT PERIOD

4.1 SUMMARY OF TASKS

The following tasks will be completed during the next reporting period, which ends 2 August 1966:

(1) Draw preliminary sketches of the 5500°F vortex valve.

(2) Draw preliminary sketches of the 5500°F supply manifold for a two-vortex valve arrangement. The manifold will be designed so the SITVC System can be mounted on the EM-72 ABL rocket motor.

(3) Inventory insulation raw stock and tungsten parts to determine needs for firings No. 4 and No. 5.

(4) Write test procedure for system firing No. 4.

(5) Define firing program for system test No. 4.

(6) Visit NASA-Langley for a program review.

4.2 PROPOSED TEST PLANS

There are two feasible test plans which will satisfy the requirements of Phase I and enhance the program objective of Phase II. Each test plan is described, and a summary of the tasks particular to both are presented. The present 2000°F SPGG will be used in both of the test plans selected as it is available. It has not been firmly established with a hot firing that a hotter pilot stage control gas is required.

TEST PLAN I

This system consists of the existing 2000°F SPGG and grain: the 5500°F SPGG with a modified aft head and two modified 5500°F vortex valves. Modifications of the 5500°F SPGG aft head will include a supply plenum chamber and a mounting pad for the vortex valves. The valves and manifold will be designed for mounting on the ABL EM-72 rocket motor. The control manifold will be designed to fit the system.

The 5500°F vortex valve will be similar to the configuration of hot gas test No. 3, except that the button cap will be the residual buttons from hot test No. 2. The valve end cap will be replaced with a retainer ring which is to be designed later. The following are the highlights of the test plan:

Test Plan I Highlights

A. Design Requirements
   1. P_o plenum chamber
   2. Injector ring
   3. Injector
   4. Supply plenum chamber
   5. Valve button, liner and insulation retainer
   6. Control manifold

B. Procurement
   1. 3 buttons
   2. 3 vortex chambers
   3. 3 P_o plenum chamber liners
   4. 16 injectors
   5. 2 button caps (tungsten)

C. Advantages
   1. Allows four firings on Phase II supply plenum manifold to establish reliability
   2. Eliminates the need for an exotic button cap design
   3. Nearly all the existing tungsten hardware can be used during hot gas tests
   4. Principle design is the same as buried nozzle injection concept for Phase II
   5. Reduces transition time between Phase I and the demonstration hot gas test of Phase II

D. Disadvantages

   Extends the duration of Phase I contract schedule because of design revisions and liaison with outside sources.

TEST PLAN II

This test plan is a combination of two system configurations: The first system will be similar to part number 2161180 shown in Figure 2 of the 2 April 1966 - 2 May 1966 progress report, except for minor design modifications to reflect the latest test results. This system configuration will be evaluated during test firing No. 4.

The second system configuration will be as described in Test Plan I. Both system configurations will utilize the presently designed 2000°F SPGG for pilot stage control. The following are highlights of the test plan:

Test Plan II Highlights

A. Design Requirements
1. Aft head exit insulator
2. Button cap
3. P_o plenum chamber
4. Injector ring
5. Injectors
6. Supply plenum manifold
7. Control flow manifold
8. Valve button, liner and insulation retainer

B. Procurement
1. 3 buttons
2. 3 vortex chamber liners
3. P_o plenum chamber liners
4. 16 injectors
5. 2 sets of valve insulators and FAB 3
6. 1 button cap insulator and FAB 2
7. 1 set control manifold and FAB
8. 1 set of supply plenum manifold insulators

C. Advantages
1. Allows demonstration of flow modulation before Phase II commitment
2. Allows time for FAB and design of Phase II manifold
3. Will provide three tests on Phase II manifold to establish reliability
4. Otherwise residual hardware will be expended
5. Will determine which control SPGG to procure for Phase II and, conversely, the need for development of a 4000°F pilot stage valve

D. Disadvantages

Development of some hardware during Phase I which may not be used in ensuing tests.

The confidence level for both test plans is high, based on the recent computer study and the tests conducted on a model vortex valve. This was a Bendix-funded effort to investigate the technical problems realized from system test firing No. 3. A more detailed description of the analysis and test is presented in Section 2.2 of this report. The tests and the study indicated that, logically, the next two tests should be system tests, utilizing the present 2000°F SPGG.

SECTION 5

PROGRAM SCHEDULE

The program schedule is being revised and will be submitted in the next monthly progress report after submission of additional costs to completion and selection of a firm test plan.

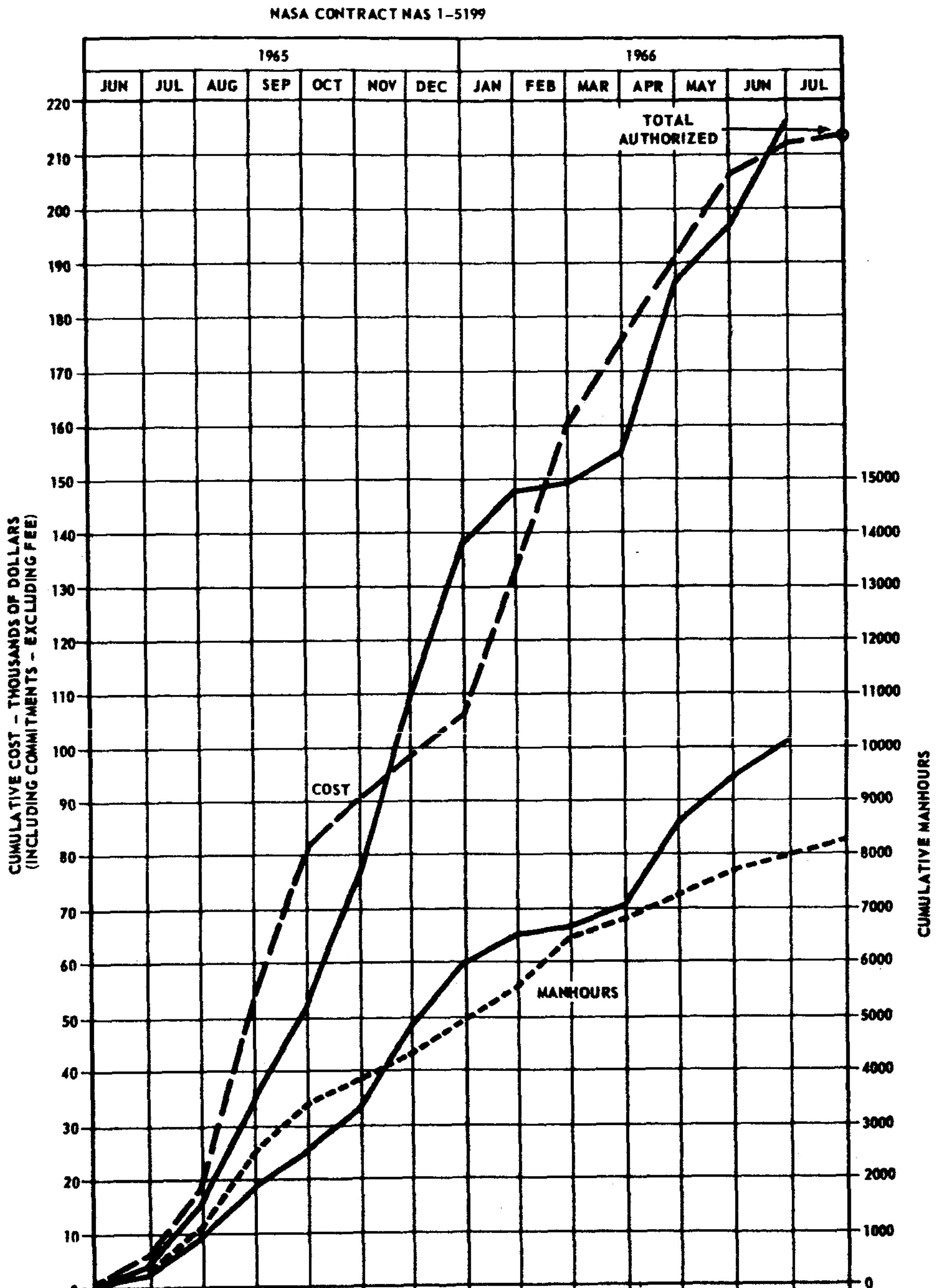
SECTION 6

MONTHLY FINANCIAL AND MANPOWER UTILIZATION REPORT

The cumulative manhour expenditures by category through June 30 are as follows:

Engineering	5151
Drafting	337
Technician	2300
Miscellaneous	929
Shop	1421

A graphic and tabular presentation of contract expenditures is shown in Figure 8.



	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL
FORECAST COST	5.08	18.26	53.21	81.23	90.76	97.82	106.28	115.74	160.1	175.0	190.7	206.6	210.9	214.0
ACTUAL COST (EXCLUDING COMMITMENTS)	4.79	15.09	29.47	48.06	60.38	90.48	116.52	134.85	136.7	156.1	180.6	197.4	214.1	
CURRENT COMMITMENTS		0.02	5.07	4.52	16.54	19.40	22.14	12.28	11.9	.2	4.6	3.2	2.5	
TOTAL COST (INCLUDING COMMITMENTS)	4.79	15.11	34.54	5258	76.92	109.88	138.66	147.13	148.6	156.3	185.2	200.6	216.6	
FORECAST MANHOURS	326	1224	2650	3465	3818	4364	4989	5644	6450	6803	7223	7660	7979	8223
ACTUAL MANHOURS	289	946	1805	2569	3311	4792	5992	6529	6567	7053	8632	9448	10,138	

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Figure 8 - Research and Development of the Vortex Valve Principle and Its Application to a Hot-Gas (5500°F) Secondary Injection Thrust Vector Control System

APPENDIX A

RESULTS OF 5500°F SITVC SYSTEM - SINGLE VORTEX VALVE TEST NUMBER 3

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RESULTS OF 5500°F SITVC SYSTEM - SINGLE VORTEX VALVE TEST NUMBER 3

The system tested was a 5500°F SITVC Single-Valve System with a 2000°F control stage. The primary test objective was to demonstrate a flow modulation of the 5500°F highly aluminized solid propellant gas using 2000°F nonaluminized solid propellant gas for control. The primary objective was to realize a single-valve system flow modulation range and compare it to the theoretical. A second, but equally important objective was to evaluate the third design configuration of the 5500°F vortex valve with respect to structural integrity of the insulation button and plenum chamber. After the latest valve design has proved satisfactory, it will permit testing a two-vortex valve complete system.

The test was conducted in two parts. The first was a steady-state cold gas test of the system and its individual components, using nitrogen as the gas source. The second was a steady-state hot gas test of the system with a 5500°F SPGG used as the hot gas supply and a 2000°F SPGG used as the source of hot control gas.

The cold gas tests of the single vortex valve and the system components showed satisfactory performance. Most of the hot gas test objectives were attained. The hot gas test indicated that the following structural problems have been corrected: thermal expansion and resulting distortion of the tungsten parts, button section failure, and load orifice retention. Items that require further design investigations are: control injectors and button cap leading edge. The hot gas performance of the vortex valve did not meet all expectations. The apparent hot gas flow turndown was 1.43 to 1. This degradation in performance is believed to be due mainly to the erosion and geometric change of the control injectors and the resulting poor momentum exchange between the control and supply hot gas.

A.1 SYSTEM DESCRIPTION

The basic schematic of the system tested is shown in Figure A-1. The vortex valve receives gas from a 5500°F hot gas generator through plenum chamber and vent orifice assembly. The vortex valve control

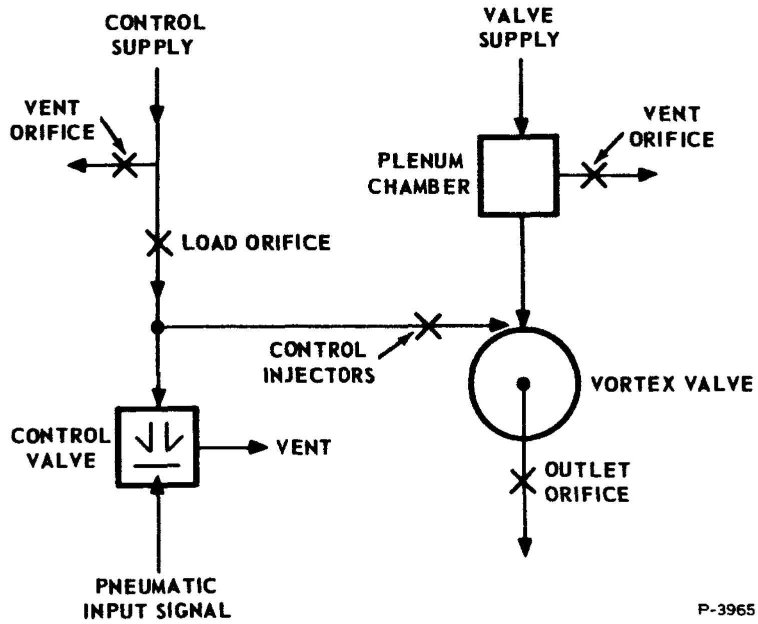

Figure A-1 - Basic Test Schematic for the Single Vortex Valve Test

flow originates in a 2000°F hot gas generator. The control flow is modulated by a vented manual control valve, which in turn is operated by a pneumatic input signal from a 2-position four-way solenoid valve.

Vortex Valve

The vortex valve, as tested, is shown in Figures A-2 through A-6. The vortex chamber, the button body, the valve load orifice and the plenum chamber, and the support ring, were all made from silver-infiltrated tungsten. All of the insulation used in the valve construction was carbon phenolic (Fiberite MX-4926). The materials used for the orifice retaining plate, the valve end cap, the valve housing, and the outlet pressure pickup adaptor were 300 Series stainless steel. The valve button assembly consisted of the carbon silica phenolic (Fiberite MXC-195) button cap retained to the silver-infiltrated tungsten button body by two press-fit forged tungsten pins. The vortex valve control injectors were made from TZM molybdenum.

Plenum Chamber and Vent Orifice Assembly

The plenum chamber and vent orifice assembly is shown in Figures A-7 and A-8. The housing for the assembly was fabricated by welding together a modified 5500°F SPGG aft closure and a plenum

QTY REQD	DWG SIZE	PART NO.	DESCRIPTION	MATERIAL DESCRIPTION & SPECIFICATION	CODE IDENT	ITEM NO.
1		STOCK	"O" RING - PARKER	SIZE #2-29 - V377-9		19
2		STOCK	'O' RING - PARKER	SIZE #2-36 - V377-9		18
4		STOCK	SCR SOC HD CAP	.312-24 UNF-3AX.62LG		17
6		STOCK	SCR SOC HD CAP	.312-24 UNF-3AX.75LG		16
4	B	2159113	INJECTOR			15
						14
1	B	2162241	SUPPORT RING			13
1	C	2162414	VALVE BODY INSULATOR			12
1	C	2162413	VALVE BODY INSULATOR			11
1	C	2161355-1	VORTEX CHAMBER			10
1	C	2162502	INSULATION - VORTEX VALVE PLENUM CHAMBER & LOAD ORIFICE			9
1	B	2162415	REDUCER PLUG			8
1	D	2159097	VALVE PORT RING ASS'Y			7
1	D	2161184	BUTTON BODY VORTEX VALVE			6
1	B	2162209	ORIFICE - VORTEX VALVE PLENUM CHAMBER OUTLET			5
1	B	2162242	BUTTON CAP VORTEX VALVE			4
1	B	2161558	EXHAUST FLANGE - VALVE			3
1	C	2161187	END CAP - VALVE ASS'Y			2
1	D	2161185-1	VALVE BODY			1

LIST OF MATERIAL

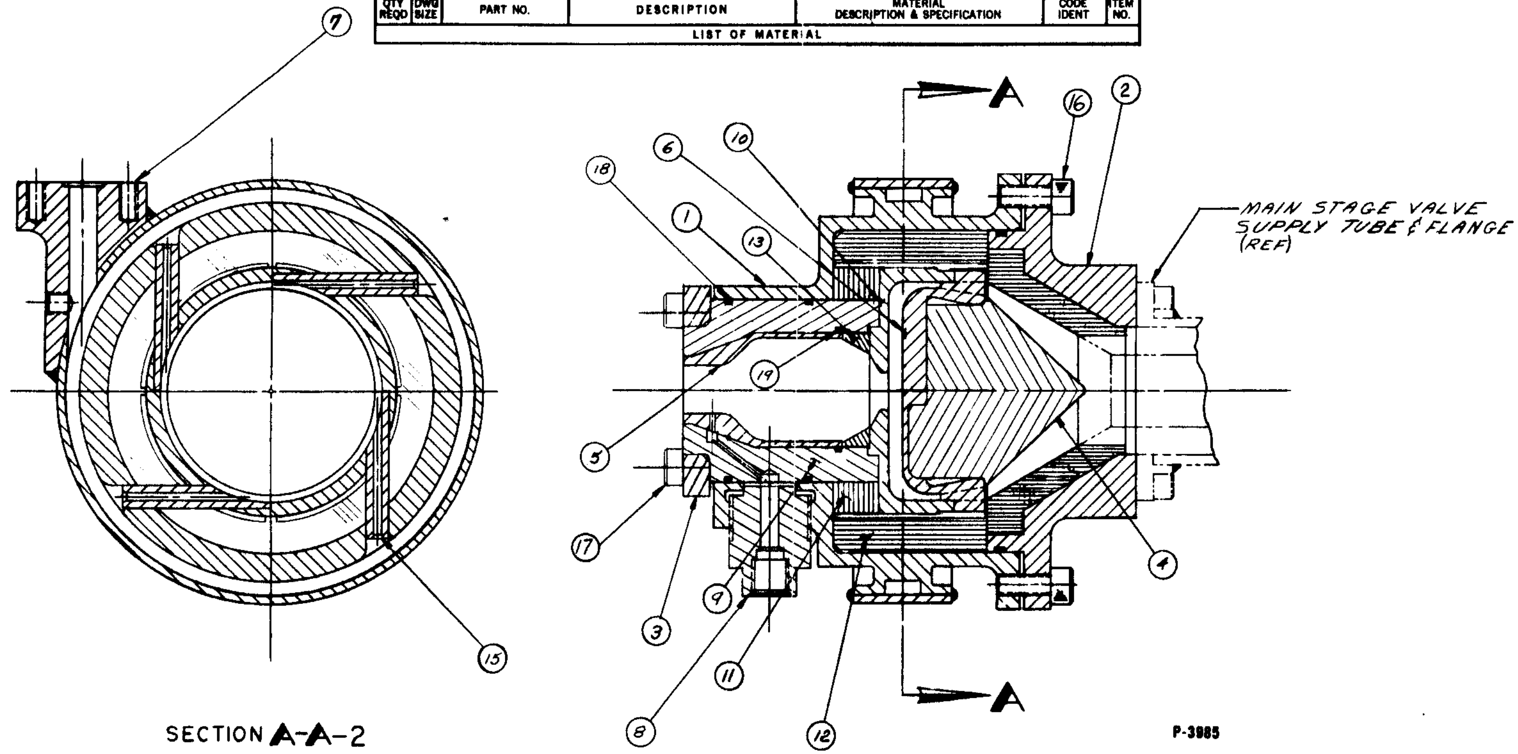

Figure A-2 - 5500°F Vortex Valve Assembly

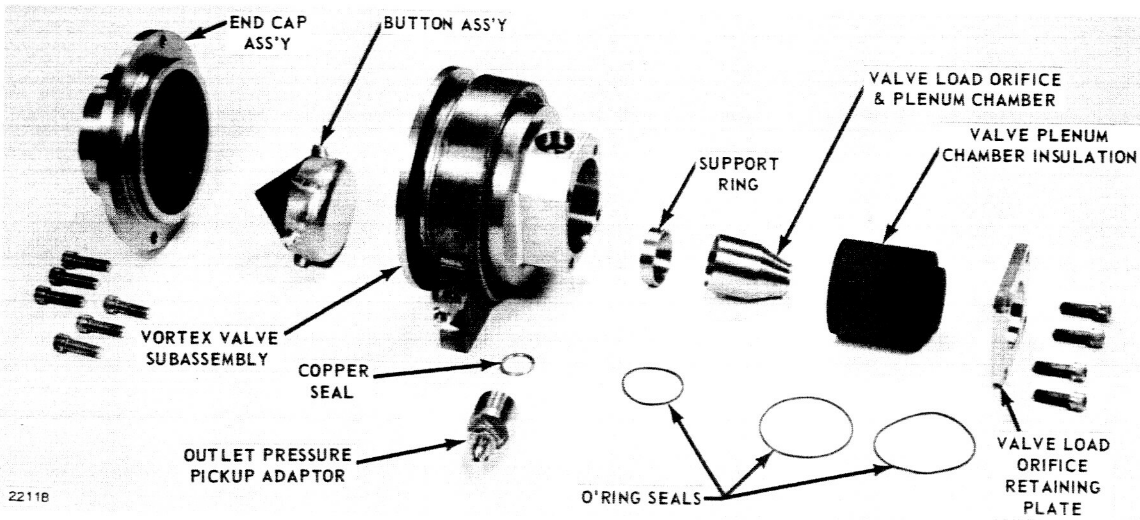

Figure A-3 - Vortex Valve Components

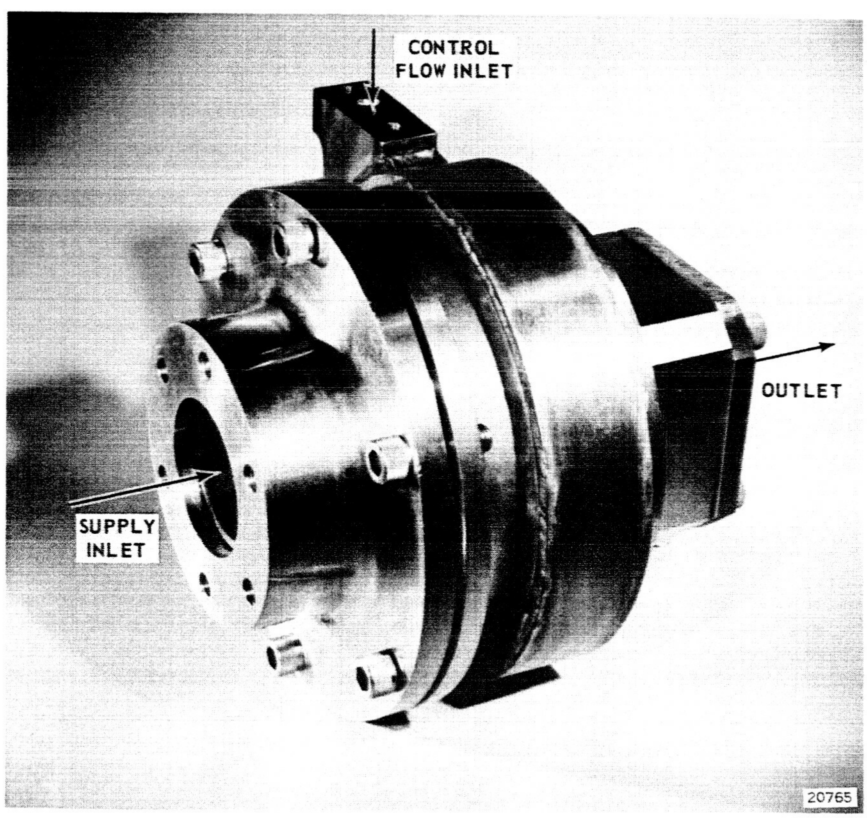

Figure A-4 - Vortex Valve Assembly

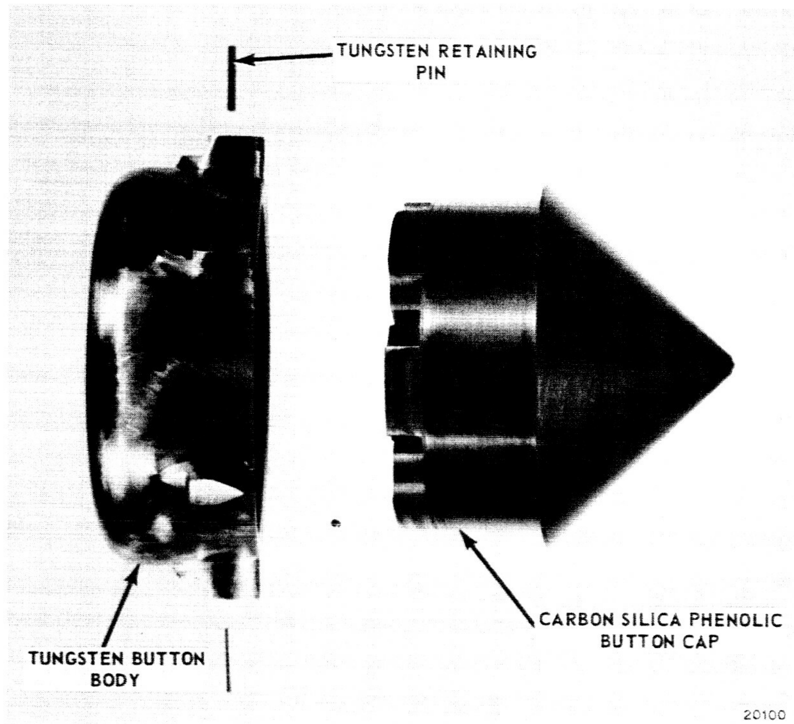

Figure A-5 - Vortex Valve Button

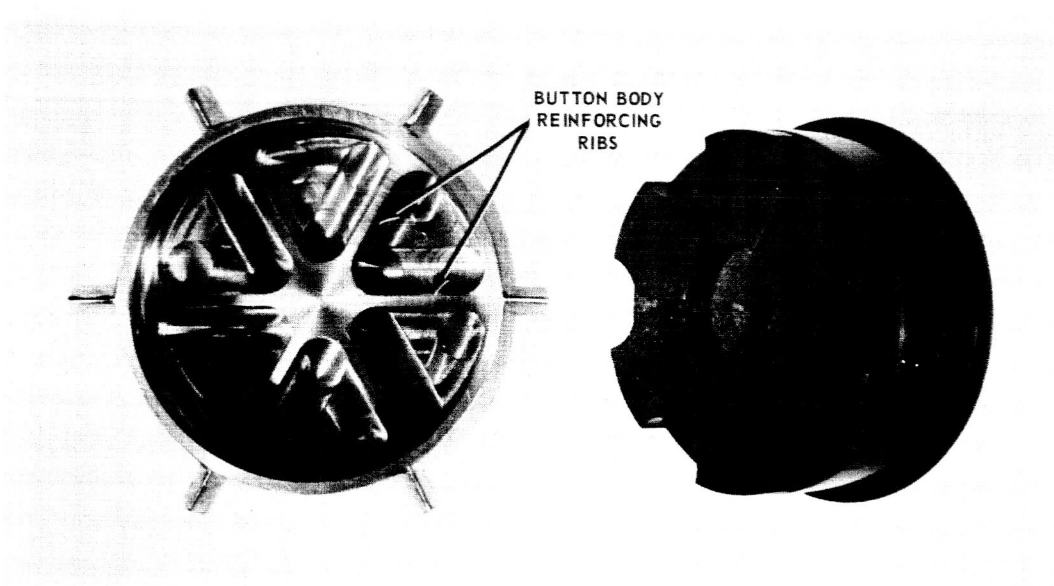

Figure A-6 - Vortex Valve Button

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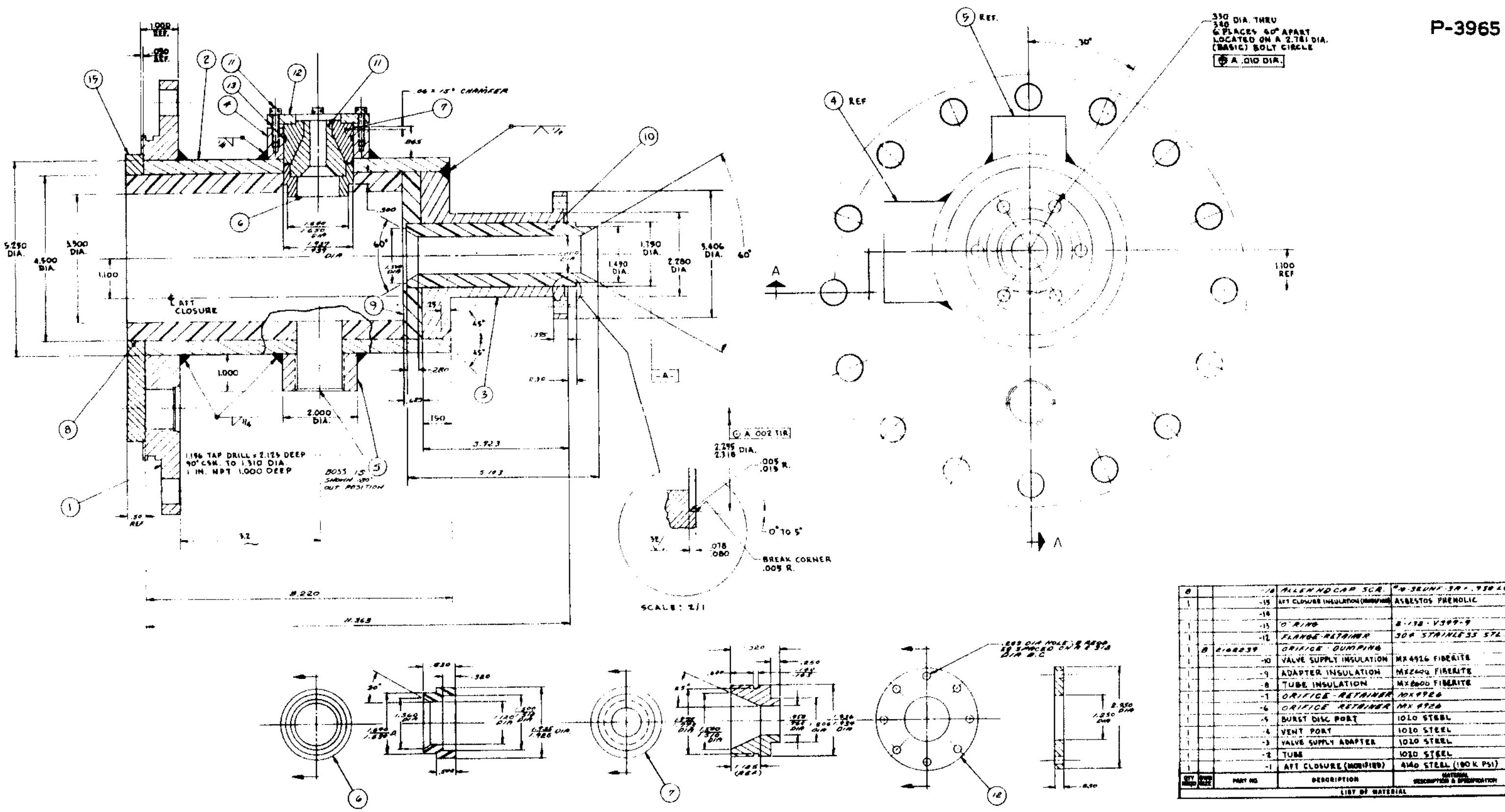


QTY REQD	DWG SIZE	PART NO.	DESCRIPTION	MATERIAL DESCRIPTION & SPECIFICATION	CODE IDENT	ITEM NO.
8		-16	ALLEN HD CAP SCR.	#10-32UNF-3A x .750 LG		16
1		-15	AFT CLOSURE INSULATION (MODIFIED)	ASBESTOS PHENOLIC	2	15
		-14				14
1		-13	"O" RING	2-138-V399-9		13
1		-12	FLANGE-RETAINER	304 STAINLESS STL		12
1	B	2162239	ORIFICE - DUMPING			11
1		-10	VALVE SUPPLY INSULATION	MX 4926 FIBERITE		10
1		-9	ADAPTER INSULATION	MX2600 FIBERITE		9
1		-8	TUBE INSULATION	MX 2600 FIBERITE		8
1		-7	ORIFICE - RETAINER	MX 4926		7
1		-6	ORIFICE RETAINER	MX 4926		6
1		-5	BURST DISC PORT	1010 STEEL		5
1		-4	VENT PORT	1010 STEEL		4
1		-3	VALVE SUPPLY ADAPTER	1020 STEEL		3
1		-2	TUBE	1020 STEEL		2
1		-1	AFT CLOSURE (MODIFIED)	4140 STEEL (180 K PSI)	2	1

LIST OF MATERIAL

Figure A-7 - Plenum Chamber and Vent Orifice Assembly

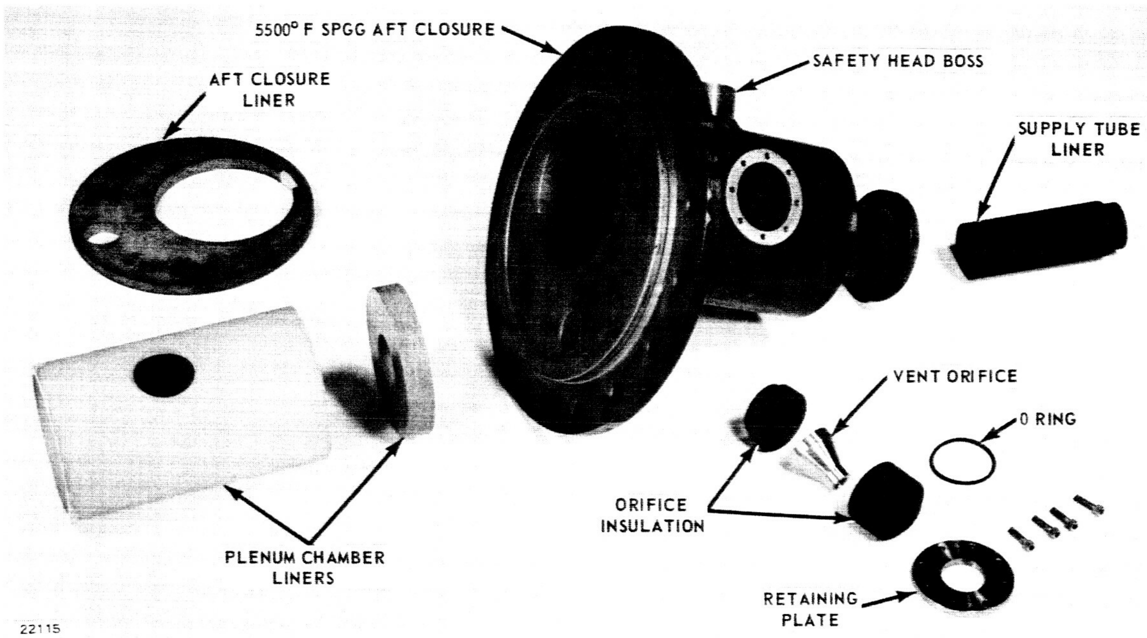


Figure A-8 - Plenum Chamber and Vent Orifice Assembly

chamber-supply tube assembly made from 1020 carbon steel. The face of the aft closure was lined with asbestos phenolic, and silica phenolic was used to line the plenum chamber. The supply tube liners and the vent orifice insulation were made from carbon phenolic. The vent orifice was made from silver-infiltrated tungsten.

A.2 COLD GAS TESTING

The purpose of the cold gas testing was to determine the steady-state performance characteristics of the single vortex valve SITVC System and to verify the intended performance of the system's various components before the hot gas test. The system's vent and flow control orifices and the control valve were calibrated in a conventional manner using nitrogen. The vortex valve and system test results are discussed below.

Vortex Valve Performance

The cold gas testing of the vortex valve was performed to obtain flow and turndown performance characteristics. The vortex valve and load orifice flow performance was obtained by flowing nitrogen through the valve assembly at various supply pressures that matched the valve's predicted operating range during the hot gas test. The data recorded were, P_o, the outlet pressure measured at the vortex valve load orifice, P_s, the valve's supply pressure; and $\dot{w}_o$, the weight flow of nitrogen through the valve. The weight flow of nitrogen was converted to an equivalent weight flow of 5500°F solid propellant and the results were plotted as $\dot{w}_o$ versus P_o, as shown in Figure A-9, and $\dot{w}_o$ versus P_s, as shown in Figure A-10.

A typical vortex valve turndown curve was obtained by varying the flow of nitrogen into the valve control injectors while regulating the valve supply flow at a constant pressure. The data obtained were plotted as $\dot{w}_o/\dot{w}_{omax}$ and $\dot{w}_c/\dot{w}_{omax}$ versus P_c/P_s, as shown in Figure A-11, in which $\dot{w}_c$ is the control weight flow and P_c is the control pressure. The total turndown obtained for the vortex valve was 5.00 to 1 at P_c/P_s equal to 1.45.

The vortex valve performance characteristics for nitrogen flow were obtained by operating with a constant P_c while P_s varied through the valve operating range. The test results for various values of P_c are shown in Figure A-12.

System Performance

The steady-state performance of the basic system shown in Figure A-1 was obtained by adding to it a pneumatic input and nitrogen to supply both stages, and then operating the system in a cold gas test. The test arrangement is shown schematically in Figure A-13.

The flow control orifice in the valve supply line was sized to provide the equivalent flow that the 5500°F SPGG would produce when the vortex valve was at full turndown. The resulting nitrogen valve supply did not duplicate the SPGG valve supply because, in an actual hot test, as the vortex valve modulates the hot gas flow, P_s will vary, causing a variation in SPGG supply flow. No variation in nitrogen supply flow occurred because of the choked orifice upstream of the vortex valve, although P_s did vary as the valve was modulated.

The valve that regulates control flow is operated in a full-open, full-closed manner as controlled by the solenoid valve. The solenoid valve was controlled from a sequencing device which produced a timed-step electrical signal.

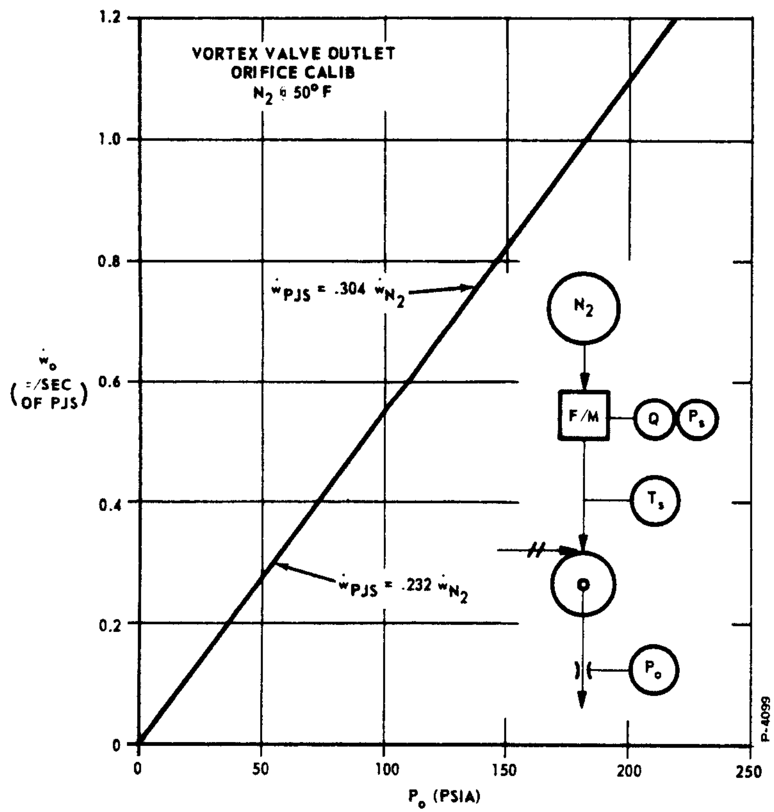


Figure A-9 - Predicted Vortex Valve and Load Orifice Flow Characteristics for PJS_C Solid Propellant Hot Gas ($\dot{w}_O$ V_S P_O)

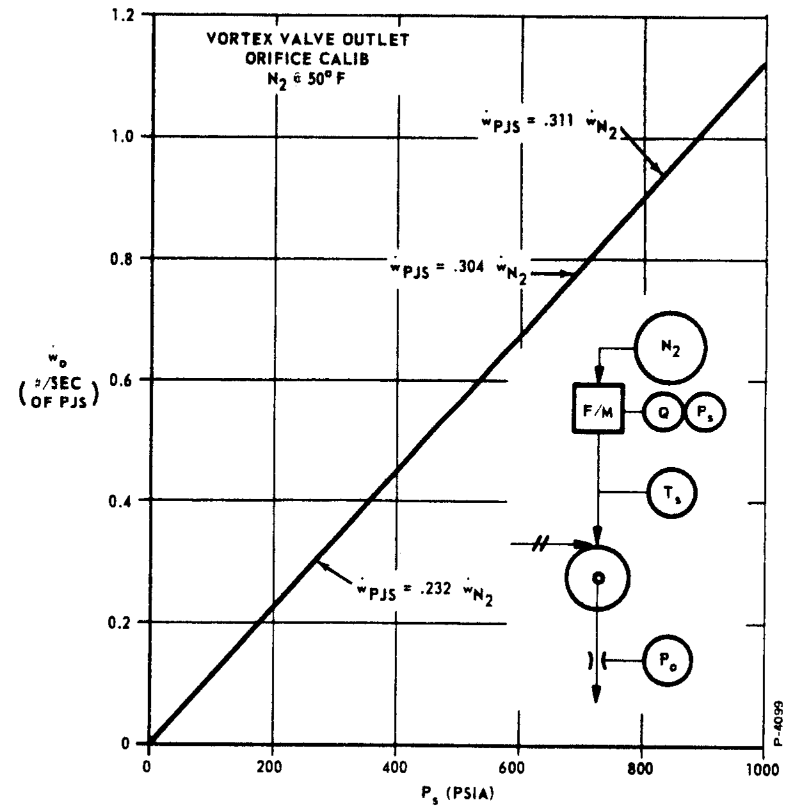


Figure A-10 - Predicted Vortex Valve and Load Orifice Flow Characteristics for PJS_C Solid Propellant Hot Gas ($\dot{w}_O$ V_S P_S)

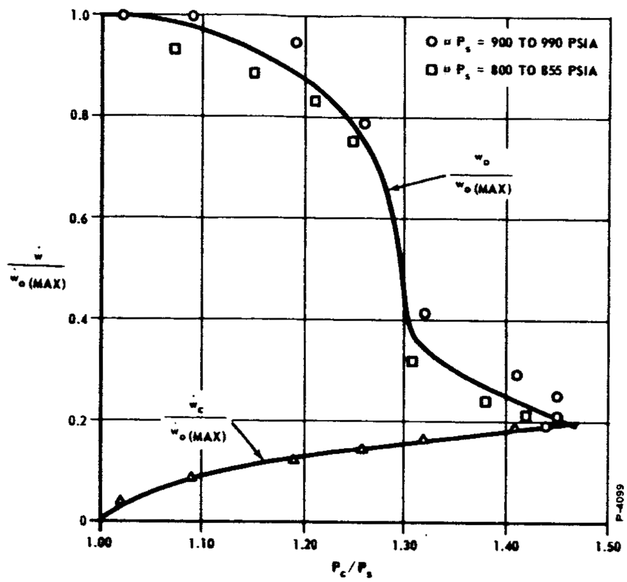


Figure A-11 - Vortex Valve and Load Orifice Turndown Performance on Nitrogen at 900 psia

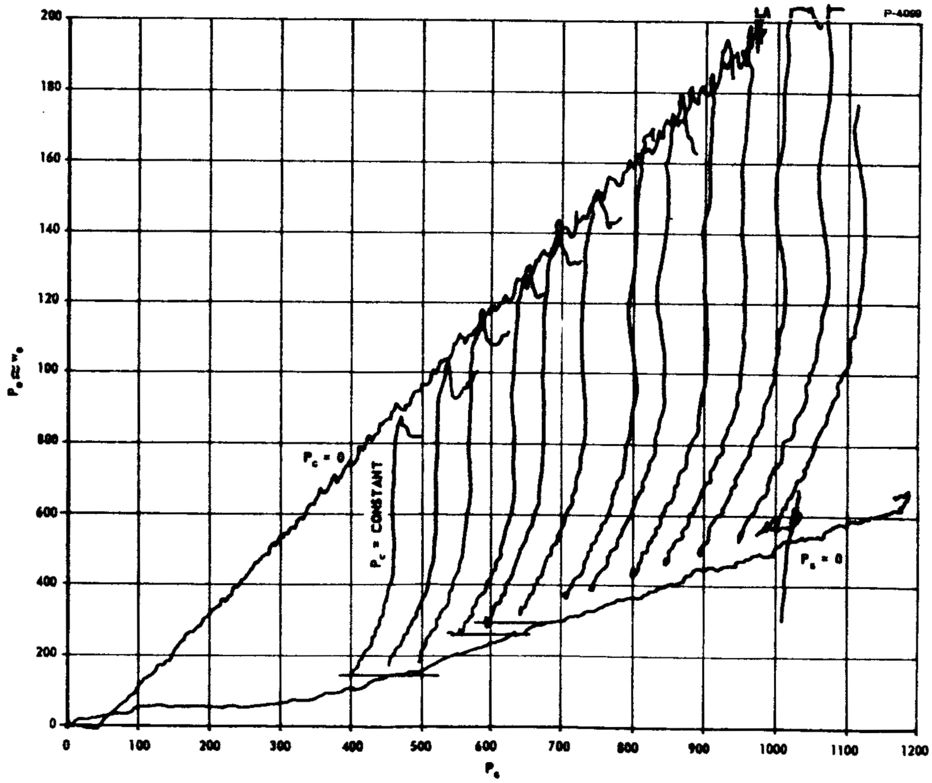


Figure A-12 - Vortex Valve Performance Characteristics using Nitrogen Gas

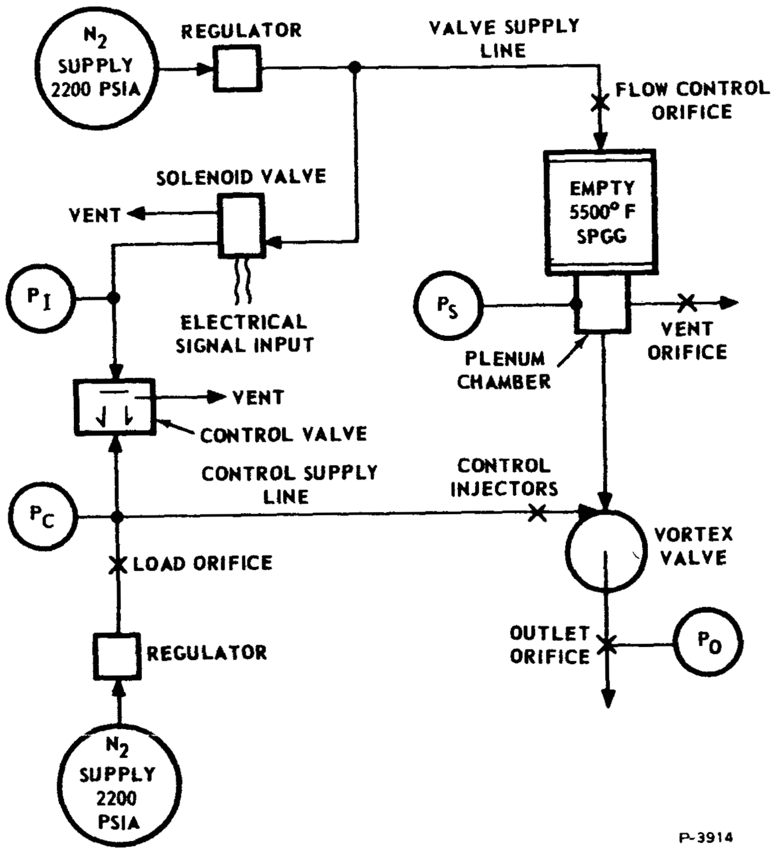


Figure A-13 - Test Schematic for Cold Gas Test of 5500°F SITVC System - Single Vortex Valve

The results of the system cold gas test are shown in Figure A-14. As can be seen, the valve supply pressure, P_s, varied as intended from 950 psia to 515 psia with a resulting variation in P_o from 65 psia to 105 psia. The resulting flow modulation from this test was 1.6 to 1. The lag in the response of the pressure P_s, P_o, and P_c from a square wave pressure input, P_I, was caused by the relatively large volume under compression in the valve supply line, and the slow response characteristic of the manual valve.

The cold gas testing indicated that the 5500°F SITVC Single Vortex Valve System would operate as predicted when coupled to the solid propellant gas generators.

A.3 HOT GAS TESTING

The purposes of the hot gas test were: (a) to demonstrate flow modulation of a 5500°F aluminized gas by using a single vortex valve

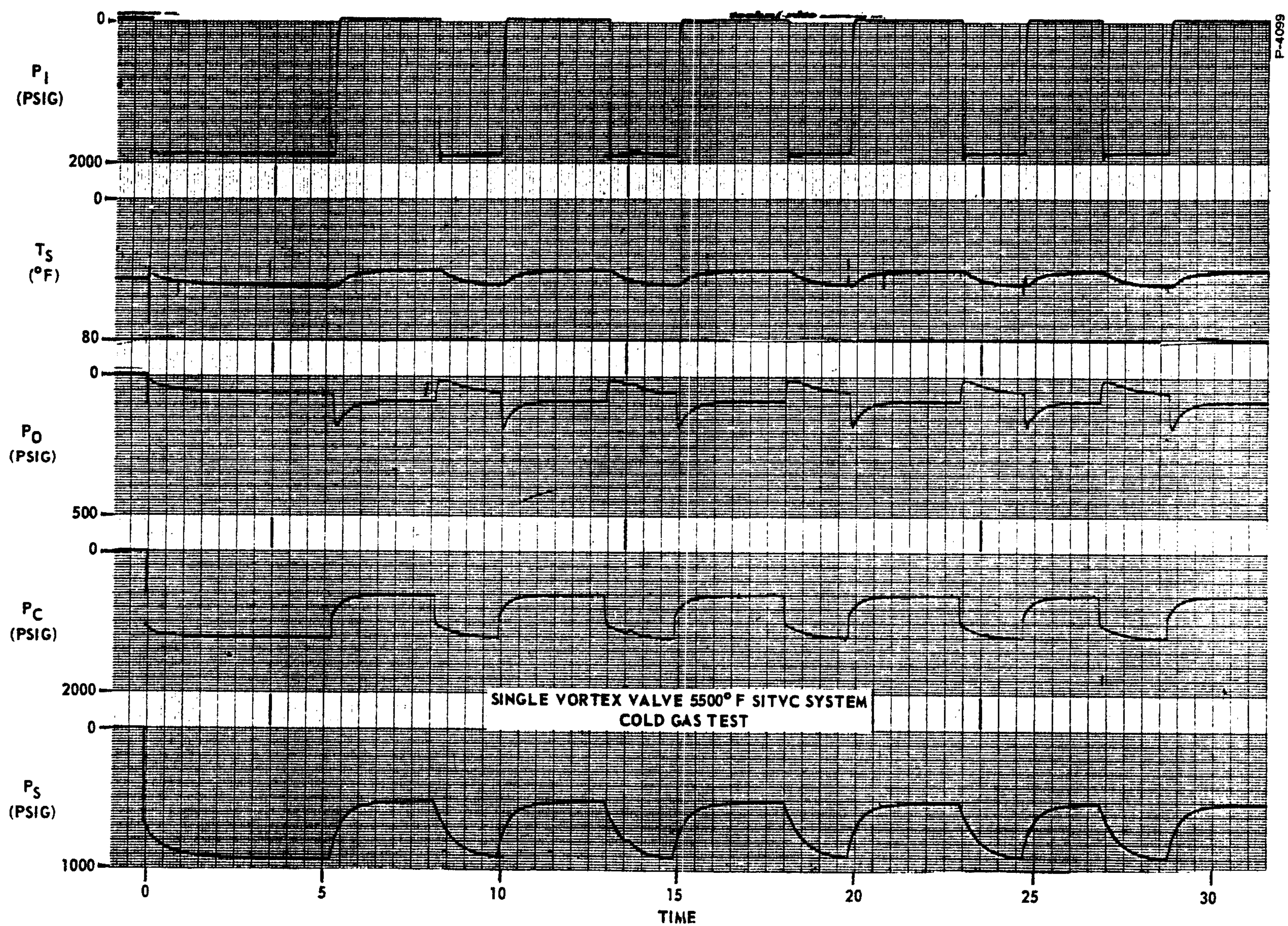


Figure A-14 - Single Vortex Valve System Cold Gas Test Results controlled by a 2000°F nonaluminized gas, and (b) to verify the structural integrity of the new vortex valve design.

Test System

The hot gas test of the basic sysem shown in Figure A-1 was obtained by adding to the basic system a pneumatic input, a 5500°F SPGG vortex valve supply, and a 2000°F SPGG control gas source. The resulting hot gas test arrangement is shown in Figures A-15 and A-16.

The supply vent orifice was sized to keep P_s max limited to 965 psia when the vortex valve was at full turndown. This was done because of control flow limitations and was determined as follows: with P_g max equal to 2265 psia, the control supply load orifice flowing sonically, and the critical pressure ratio of 0 max propellant being 0.547, the value of P_c max was found to be:

$$P_{c_{max}} = P_g \left.\frac{P_d}{P_a}\right._{crit} = 2265 \times 0.547 = 1235 \text{ psia}$$

The P_c/P_s ratio required to obtain full vortex valve turndown with the stainless steel valves was found to be 1.28, thus P_s max is

$$P_{s_{max}} = \frac{P_{c_{max}}}{1.28} = \frac{1235}{1.28} = 965 \text{ psia} \quad .$$

The 2000°F SPGG load orifices were sized to obtain the desired maximum control flow to the vortex valve. The stroke of the control valve was sized to obtain the amount of vortex valve control flow that would result in limiting P_s min to 515 psia. The supply pressure, P_s, was limited to not less than 515 psia to avert uneven 5500°F SPGG burning at low pressures and to prevent snuffing out of the SPGG from large rapid decays in supply pressure during the switching mode.

The load on the 2000°F SPGG is independent of the vortex valve's control flow. This independence exists because the 2000°F SPGG's load orifices always are at sonic conditions during the control valve's switching mode.

The "sequencer" used for controlling the cold gas tests was also used to control all events of the hot gas test. The sequencer was designed to start the required cameras, recorders, timers, to ignite the two SPGG's, and to operate the control solenoide valve at predetermined timed intervals.

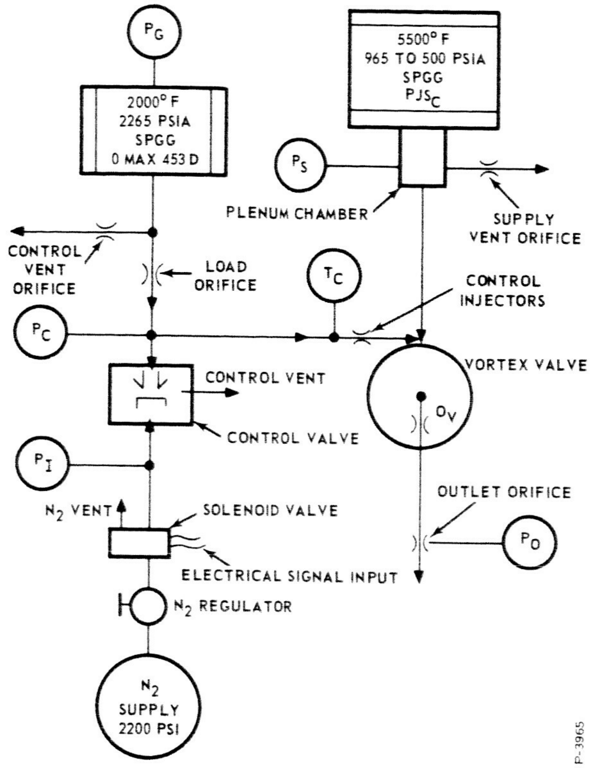


Figure A-15 - Test Schematic Hot Gas Test of 5500°F SITVC System - Single Vortex Valve

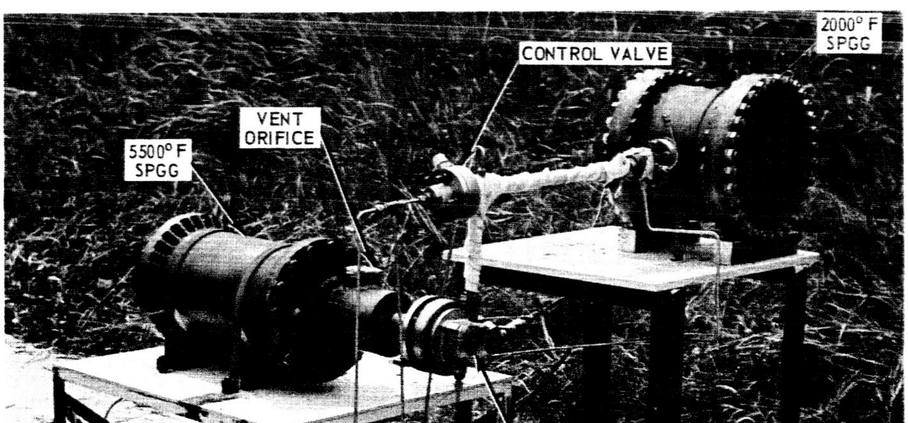


Figure A-16 - 5500°F SITVC System - Single Vortex Valve Hot Gas Test Arrangement

Test Results

All of the single-vortex-valve 5500°F SITVC System components performed their intended functions for the duration of the hot gas test. However, hot gas flow modulation performance of the system was less than expected. The test data obtained is shown in Figures A-17 and A-18. Figure A-17 is a reproduction of the actual data as recorded on a strip chart. Figure A-18 is a plot of vortex valve control pressure, P_c, supply pressure, P_s, and outlet pressure, P_o versus test time, t.

In the following discussion, the hot gas flow through the vortex valve and the plenum chamber vent orifice were calculated from individual calibration curves which were obtained from the cold gas tests.

The SPGG output flows in the following discussions were determined from equation (A-1).

$$\dot{w}_g = A \rho r = A \rho c P^n \qquad \text{(A-1)}$$

where

$\dot{w}_g$ = propellant weight flow (lb/sec)

A = area of the grain = 48 in^2

ρ = propellant density = 0.0637 lb/in^3

r = burn rate (in/sec)

c = constant dependent on grain conditioning

n = 0.3 (constant dependent on grain material)

P = generator burn pressure (psia)

The value of constant c, was calculated by first determining that the average SPGG burn pressure, $\overline{P}$, was 582 psia from the plot of P versus time in Figure A-15. Then the average weight flow of propellant for the test was found by:

$$\overline{\dot{w}}_g = \frac{\text{grain wt}}{\text{total burn time}} = \frac{42.25}{47.6} = 0.888 \text{ lb/sec.}$$

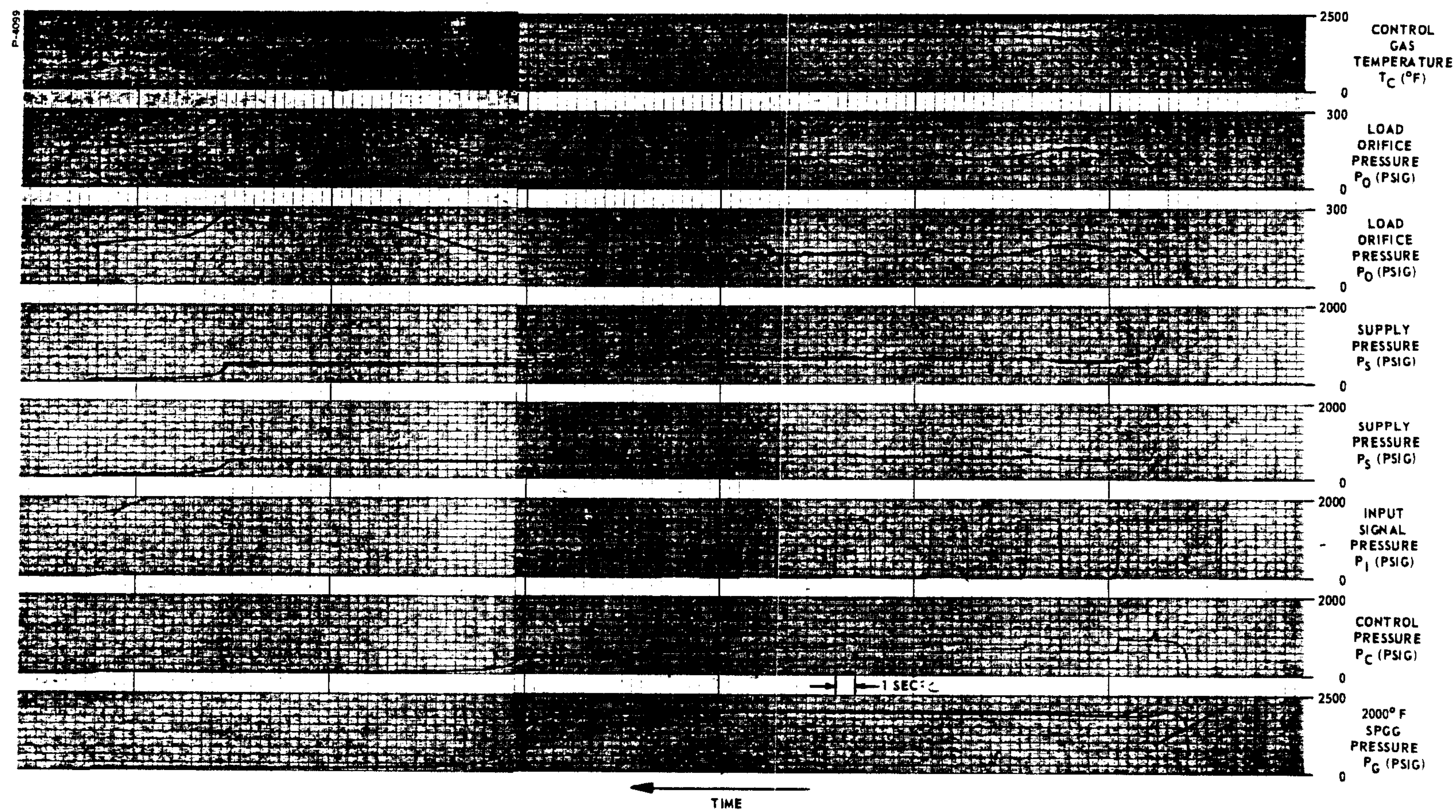


Figure A-17 - 5500°F SITVC System - Single Vortex Valve Hot Gas Test Results

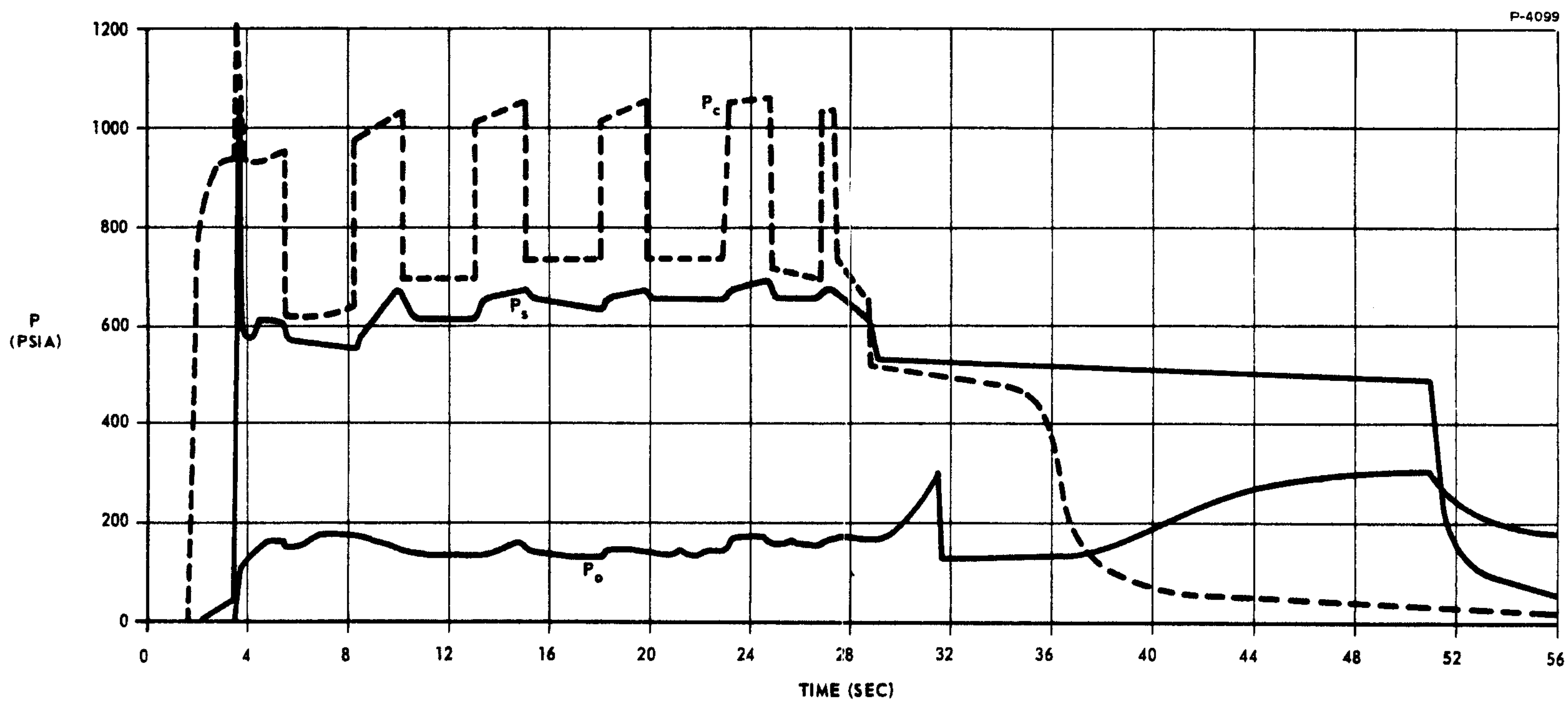


Figure A-18 - 5500°F SITVC System Single Vortex Valve Hot Gas Test Results

With the use of $\bar{\dot{w}}_g$ and $\bar{P}$ and equation (A-1) the test value of c was found to be:

$$c = \frac{\bar{\dot{w}}_g}{A \rho P^n} = \frac{0.888}{48(0.0637)582^{0.3}} = 0.0428$$

This value of c was used to calculate a burn rate as follows:

$$r_{(calc.)} = c\ P^{\ n} = 0.0428(582)^{0.3} = 0.290 \text{ in/sec}$$

The 5500°F SPGG performance for this test was compared with SPGG performance of the two previous Bendix hot gas tests and with the Hercules Powder Company ballistics test and projected performance. This comparison was made by plotting grain burn rate, r, versus SPGG mean burn pressure, $\bar{P}$, on log-log coordinates as shown in Figure A-19. This comparison indicates the 5500°F SPGG varies from the Hercules Powder Company's predicted performance at low burn pressures.

In reviewing the past 5500°F SPGG performance, it was discovered that the test value for the SPGG weight flow coefficient, C_w, is 0.00636 sec^{-1}, which is more than the Hercules specified value of 0.00619 sec^{-1}. This difference in C_w produces an error in the previously used values for the SPGG gas constant, C_2, and cold-to-hot gas flow correlation constant. A revised list of the 5500°F SPGG properties is given below:

<u>5500°F SPGG Properties</u>

(grain density)	= 0.0637 lb/in^3
M.W. (molecular weight)	= 19.96 lbm/lb-mole
T (breech temp.)	= 5760°F (6220°F)
k (ratio sp. ht.)	= 1.13
C_w (weight flow coef.)	= 0.00636 sec^{-1}
C_2 (gas const.)	= 0.556 °R/sec
n (pressure exp. in $r = cP^n$	= 0.30
$\dot{w}_{pjs_c}$	= 0.311 $\dot{w}_{n_2}$ (cold-to-hot gas flow correlation for sonic flow)

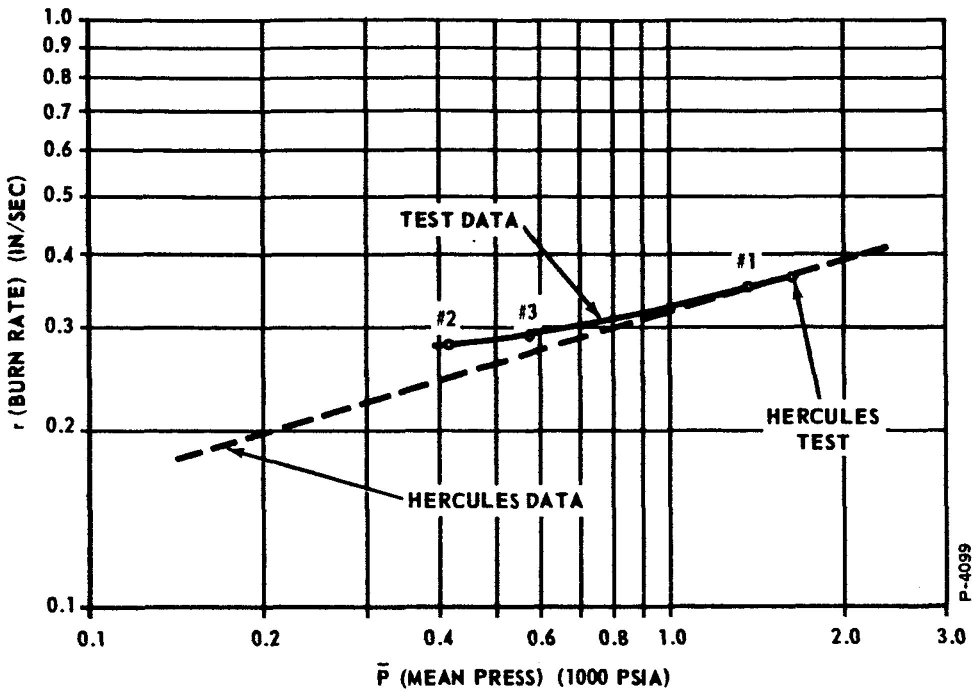


Figure A-19 - 5500°F SPGG Performance

At recorded time of 1.6 seconds, the 2000°F SPGG ignited. In the first 1.3 seconds of burning, the SPGG reached a peak breech pressure, P_g, of 2015 psia. After 1.8 seconds of burning, the SPGG pressure, P_g, dropped to 1900 psia and remained relatively constant at this value. The SPGG average burn pressure was 1900 psia for a total burn time of 33.4 seconds. The resulting average burn rate was 0.116 in/sec, and the average flow rate was 0.48 lb/sec. The average SPGG pressure, P_g, was lower than the intended pressure of 2265 psia. This lower SPGG pressure, P_g, was the reason that the vortex valve control pressure, P_c, never reached its calculated value of 1235 psia. The 2000°F SPGG performance in this test was more constant than previous 2000°F SPGG tests- with regard to neutral burning in particular, the last two hot-gas tests. This improvement in performance indicates that the previous erratic performances were due to defective grains, inasmuch as the only variable for all of the tests has been the grains.

At 3.4 seconds, the 5500°F SPGG ignited and produced a pressure spike of 1050 psia. At 5.4 seconds, the system started its first modulation cycle, which lasted 10 seconds. The remaining four cycles were very similar to the first cycle.

In compiling a flow balance between the system's various components at various test times, the fact became apparent that P_o did not provide satisfactory flow correlation for the vortex valve. This can be illustrated by reviewing the test data at time 8 seconds. At this time, the 5500°F SPGG had an outlet of 0.87 lb/sec and the vent orifice was flowing 0.52 lb/sec. These figures indicate that the vortex valve was receiving 0.43 lb/sec of hot gas. The cold-gas test data indicates that the vortex valve flow for P_o = 175 psia is 0.96 lb/sec. Thus, P_o indicated that the valve flow is greater than the SPGG output. This condition remains throughout the test. The deficiency in P_o flow correlation was attributed to vortex valve plenum chamber buckling and is discussed in the material and design evaluation section.

The first modulation cycle, from time 5 seconds to 11 seconds is shown in Figure A-20. Also shown in this Figure is the theoretical value of P_s for corresponding test values of P_c. At time 8 seconds, the actual P_c/P_s ratio was 1.14 and the apparent vortex valve turndown was 1.43 to 1. At this time, a P_c/P_s ratio of 1.25 was predicted and the corresponding valve turndown should have been 1.54 to 1. The hot gas turndown was 7 percent less than the theoretical turndown at this time.

At time 10 seconds, P_c/P_s (actual) was equal to 1.5 and the resulting apparent valve flow turndown was 1.42 to 1. The calculated valve for P_c/P_s was 1.3, which would have resulted in a predicted turndown ratio of 4.05 to 1. The hot gas turndown was 65 percent less than the theoretical turndown at this time.

Material and Design Evaluation

The generally good post-firing condition of the test hardware is shown in Figures A-21, A-22, and A-23. The vortex valve load orifice and the vent orifice remained open with no distortion. The only exterior portion of the hardware to suffer any ill effects from the hot gas test was the vortex valve control port ring. This part burned through in two places and distorted into a barrel shape as can be seen in Figure A-24 and A-25. This failure was due to backflowing of the 5500°F vortex valve supply gas through the control injectors after the burnout of the 2000°F SPGG. Evidence of this supply gas backflow is the aluminum oxide buildup on the upstream side of the injectors, as shown in Figure A-25. This problem can be overcome by a redesign of the control port ring, by matching the burn time of the 2000°F and the 5500°F SPGG's, or by introducing a nitrogen source into the control system at the time of the 2000°F SPGG burnout.

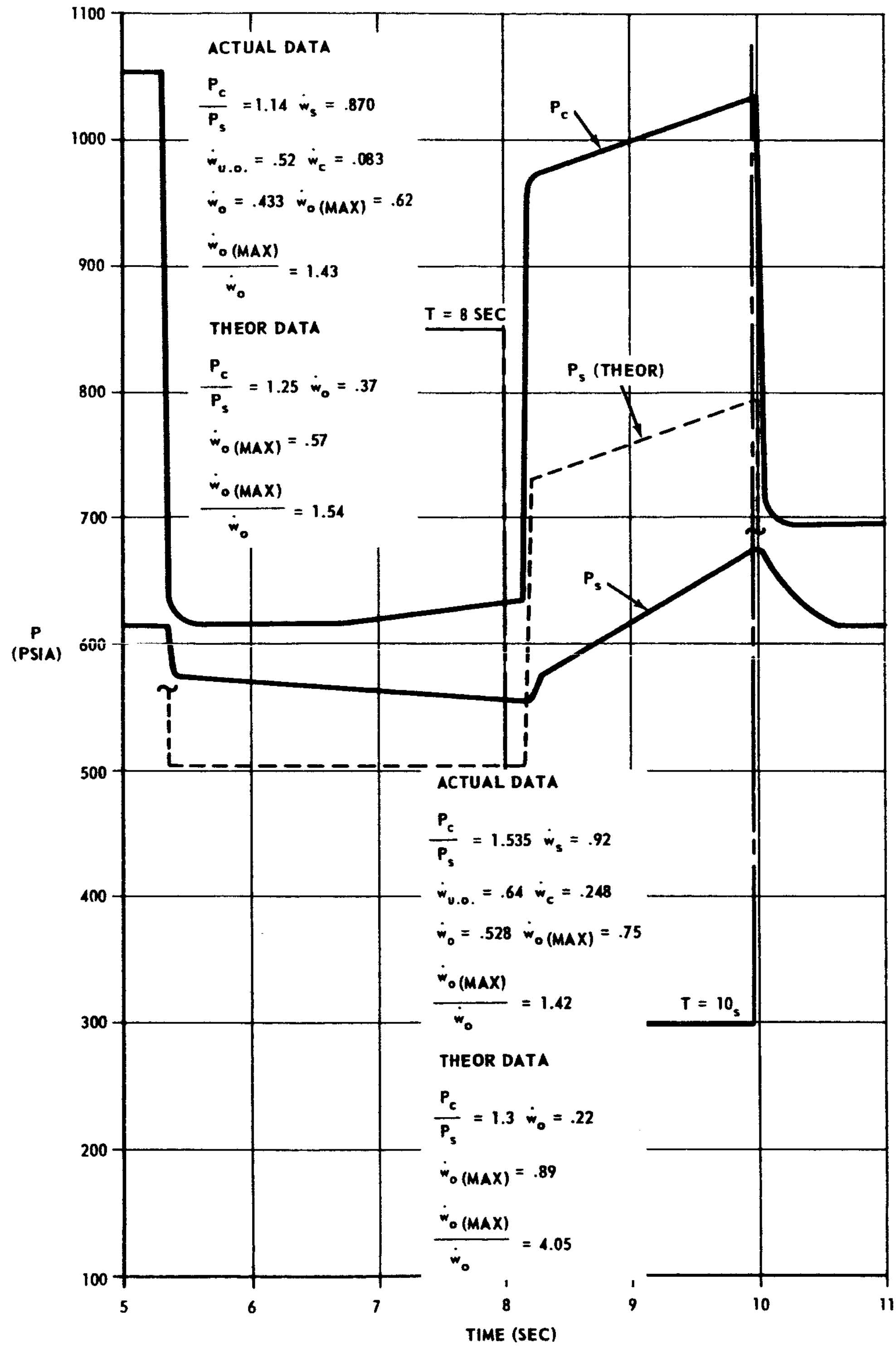


Figure A-20 - First Modulation Cycle of Hot Gas Test

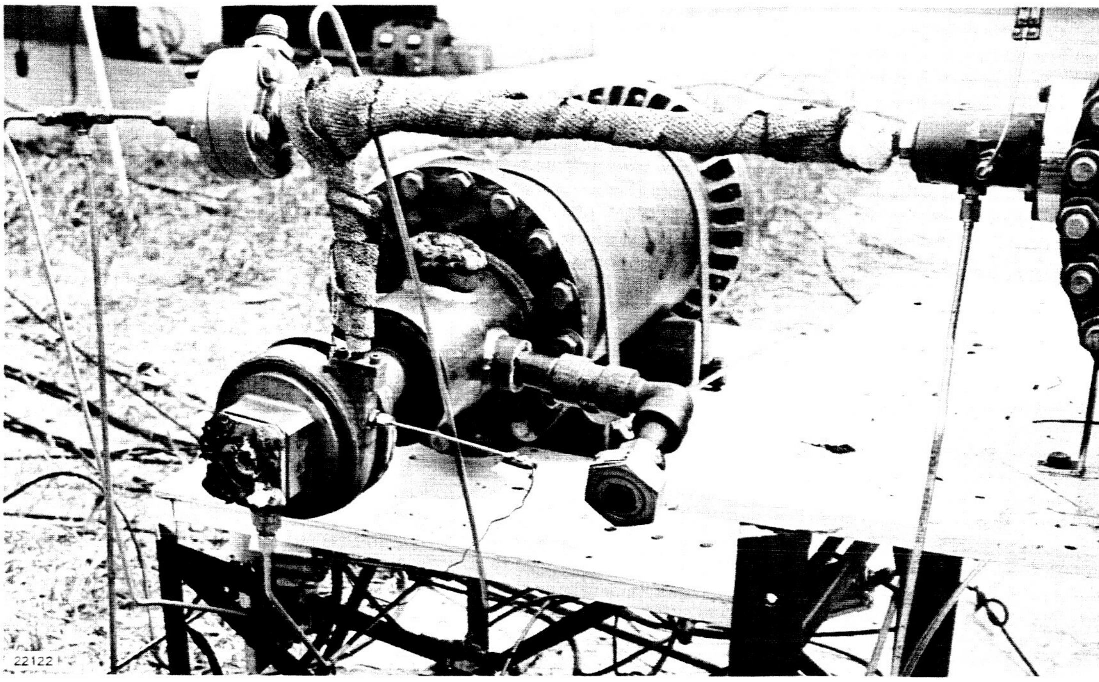


Figure A-21 - 5500°F SITVC System - Single Vortex Valve (Post Firing)

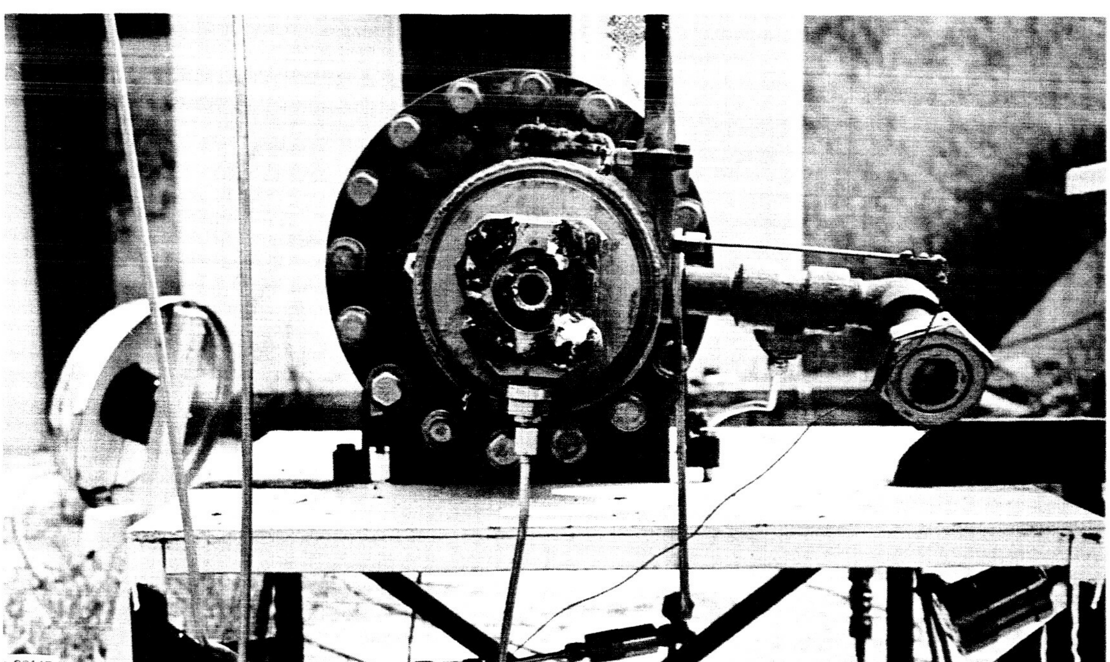


Figure A-22 - 5500°F SITVC System - Single Vortex Valve (Post Firing)

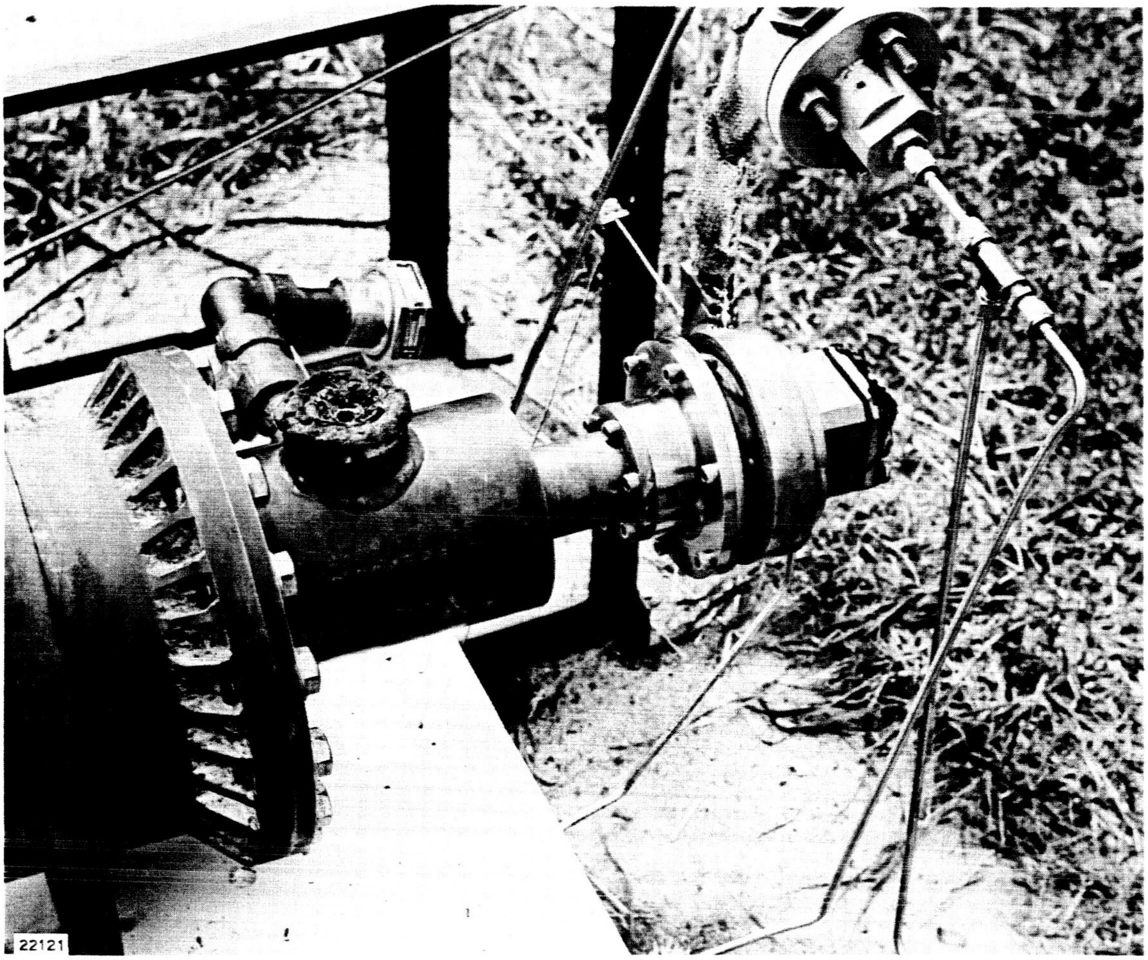
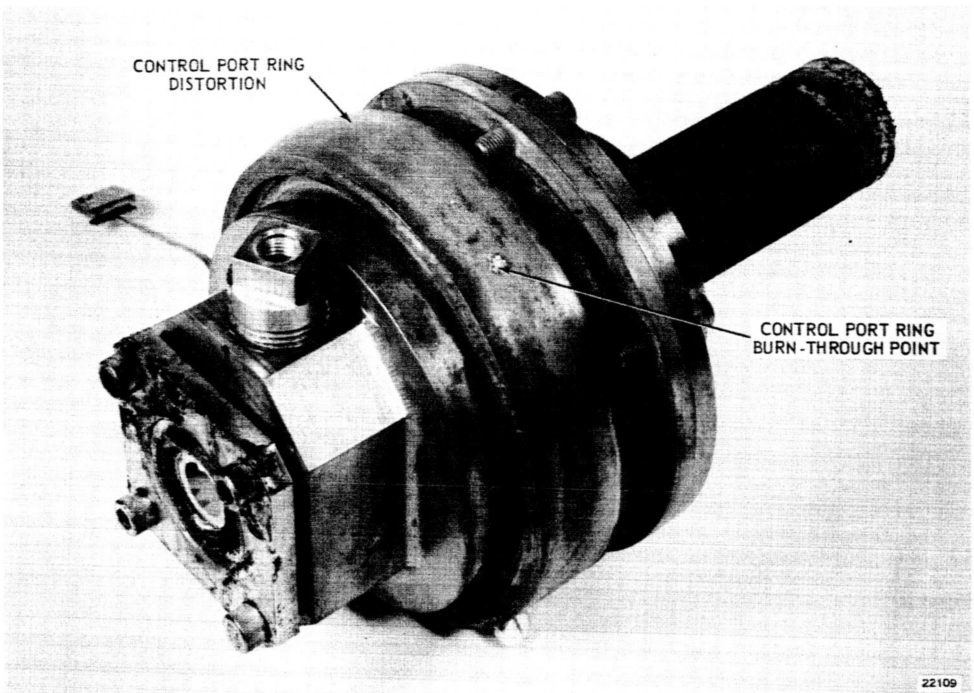


Figure A-23 - 5500°F SITVC System - Single Vortex Valve (Post Firing)

The vortex valve end cap insulation experienced some erosion as shown in Figure A-26. The resulting erosion pattern is eccentric to the original part configuration with the greatest erosion at the top of the valve. This eccentric erosion pattern matches the eccentric erosion of the valve insulation and button cap as shown in Figures A-27 and A-28. The eccentric erosion pattern appears to have been the result of irregular hot gas flow patterns that were set up by the uneven erosion of the button cap.

The downstream face of the button body developed a crack during the test (Figure A-29). This crack appears to be the result of gases trapped between the button body and cap.



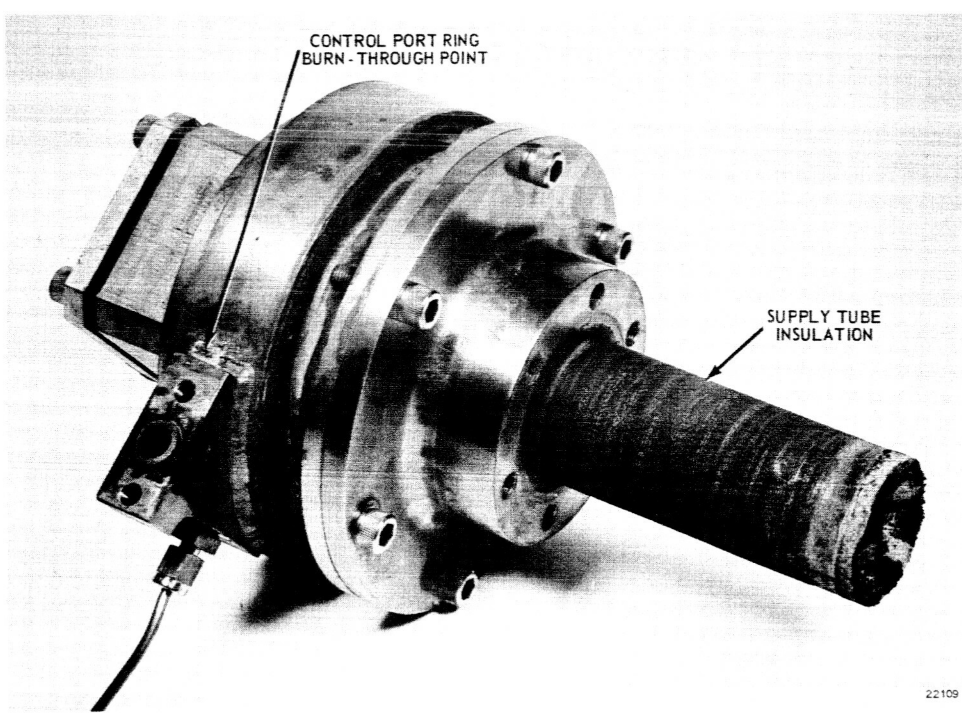


Figure A-24 - Two Views of Vortex Valve (After Test)

Figure A-25 - Vortex Valve Without Control Port Ring (Post Test)

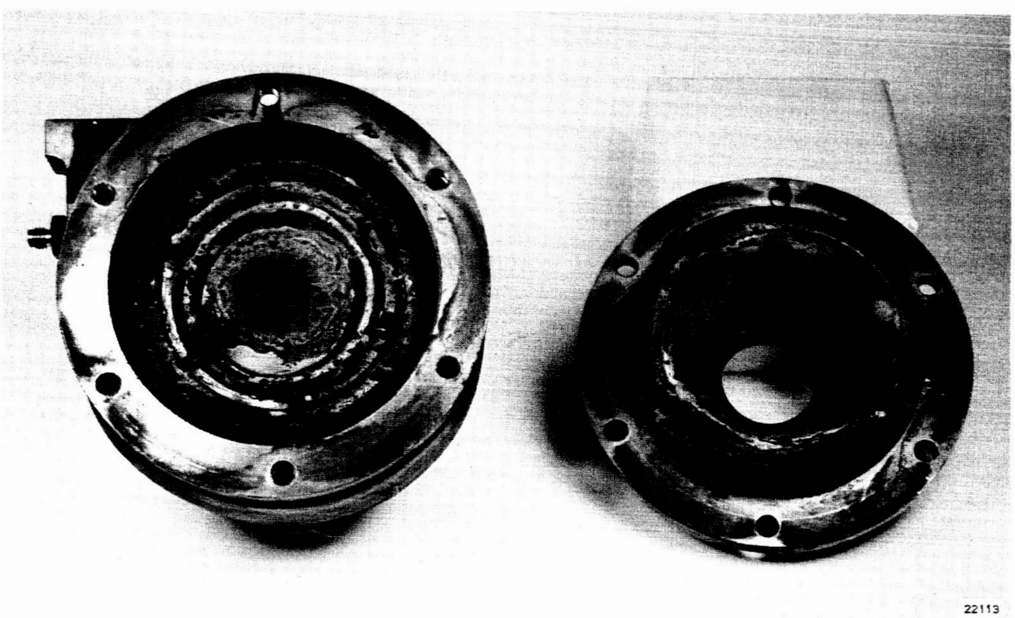


Figure A-26 - Vortex Valve and End Cap (Post Firing)

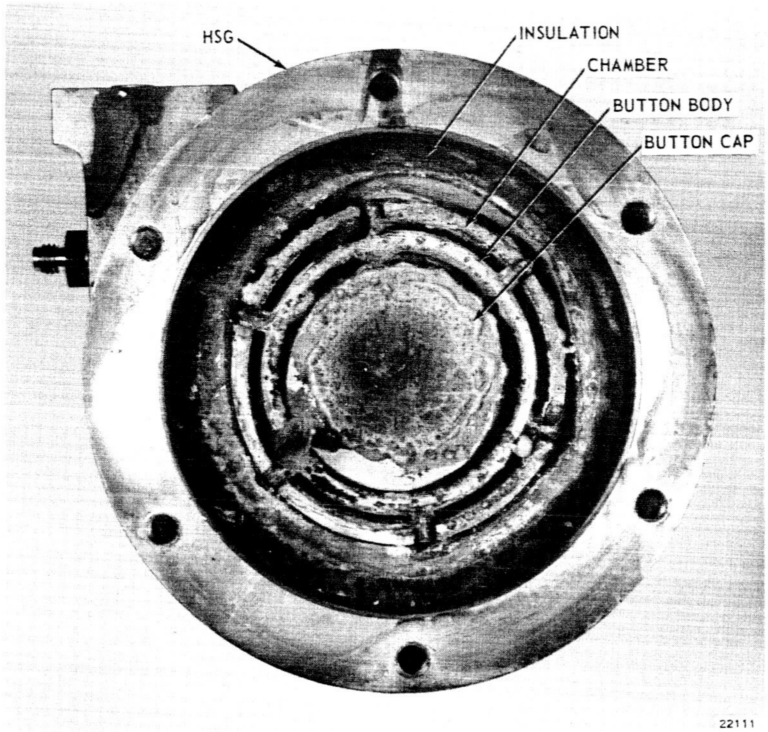


Figure A-27 - Vortex Valve HSG, Chamber, and Button (Post Firing)

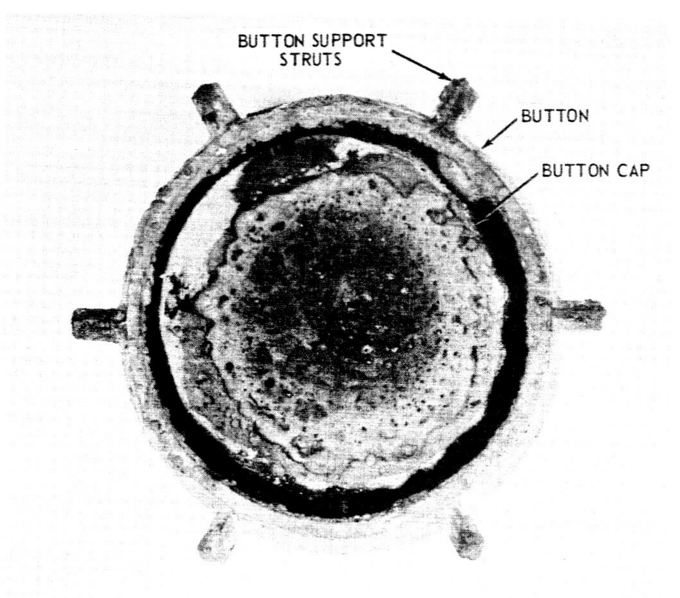


Figure A-28 - Vortex Valve Button Assembly (Post Firing)

The valve vortex chamber and outlet orifice did not experience any expansion distortion but did generate a crack as shown in Figure A-30. This crack appears to have been caused by gases trapped between the chamber and the expansion grooves in the valve insulation.

The vortex valve injectors were eroded approximately 0.75 inch back from the vortex chamber wall. The cause of the loss of the injectors was that the molybdenum injector material has too low a melting temperature for this application.

The vortex valve load orifice withstood the test with no apparent erosion, distortion or leaks, as is evidenced from Figures A-31 and A-32. The valve plenum chamber buckled from thermal expansion in one spot. This plenum chamber distortion may have been the cause of the erratic reading of P_o. Flow correlation was achieved by flow balance, using upstream measured pressures.

The system vent orifice and insulation withstood the test well, as is shown in Figures A-33, A-34 and A-35. The orifice and insulation assembly did not leak and the orifice remained undistorted during the test.

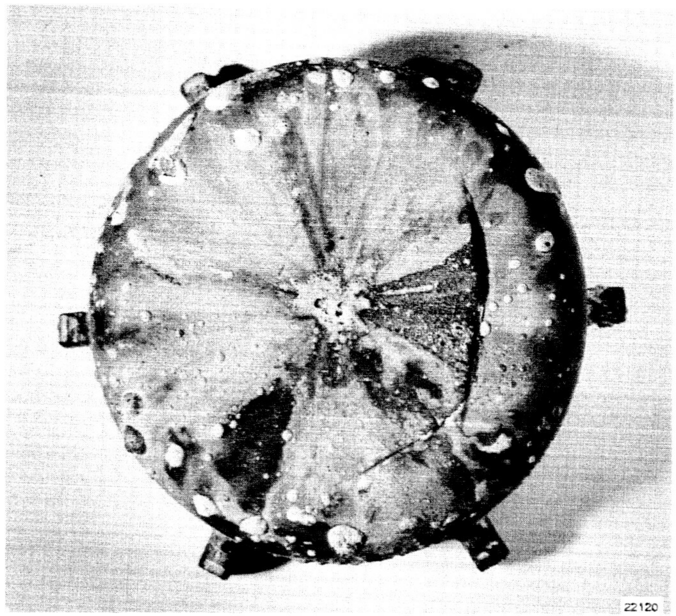


Figure A-29 - Vortex Valve Button Face (Post Firing)

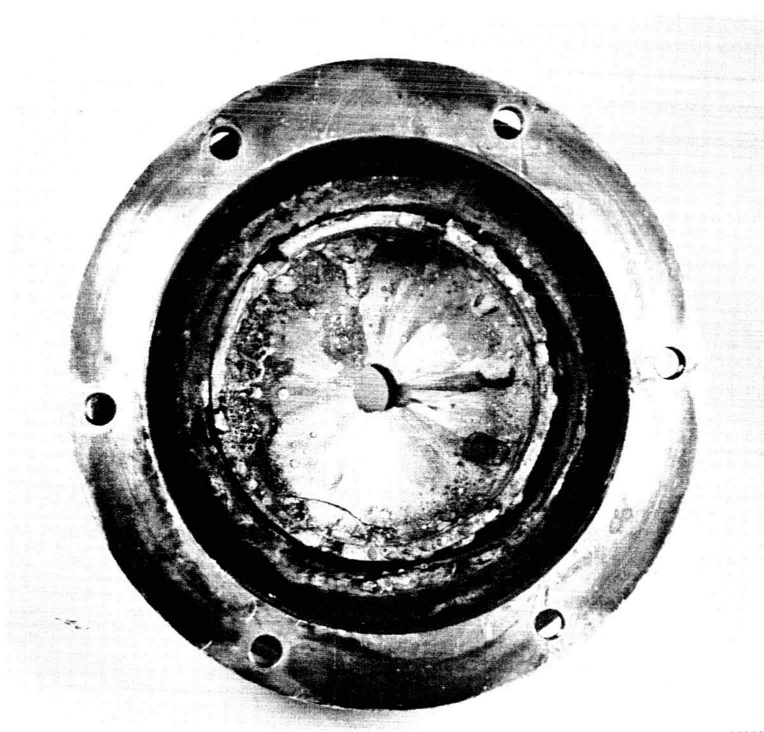


Figure A-30 - Vortex Valve Chamber (Post Firing)

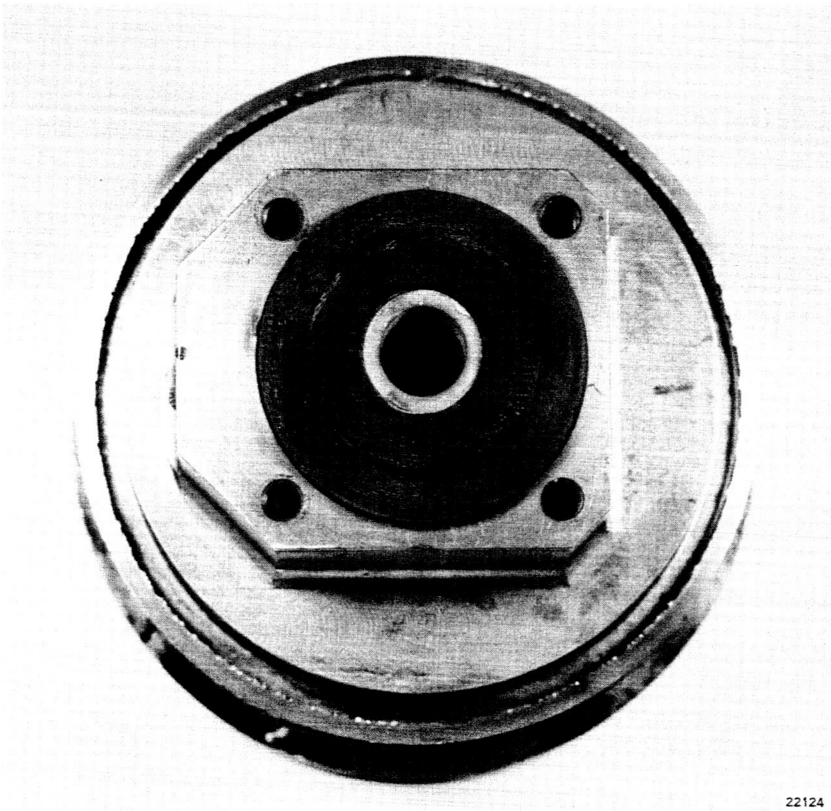


Figure A-31 - Vortex Valve Load Orifice (Post Firing)

Figure A-32 - Vortex Valve Load Orifice, Plenum Chamber and Insulation (Post Firing)

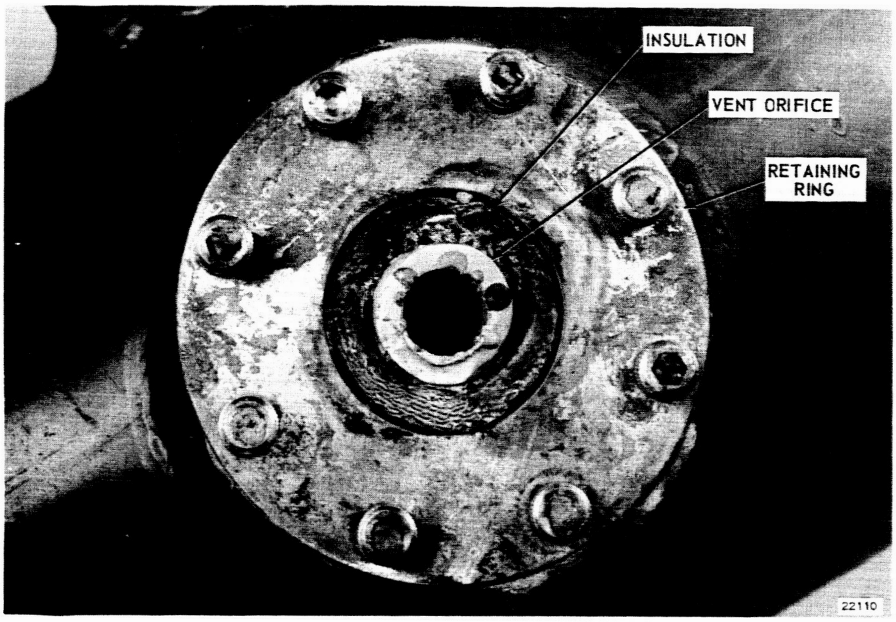


Figure A-33 - System Vent Orifice Assembly (Post Firing)

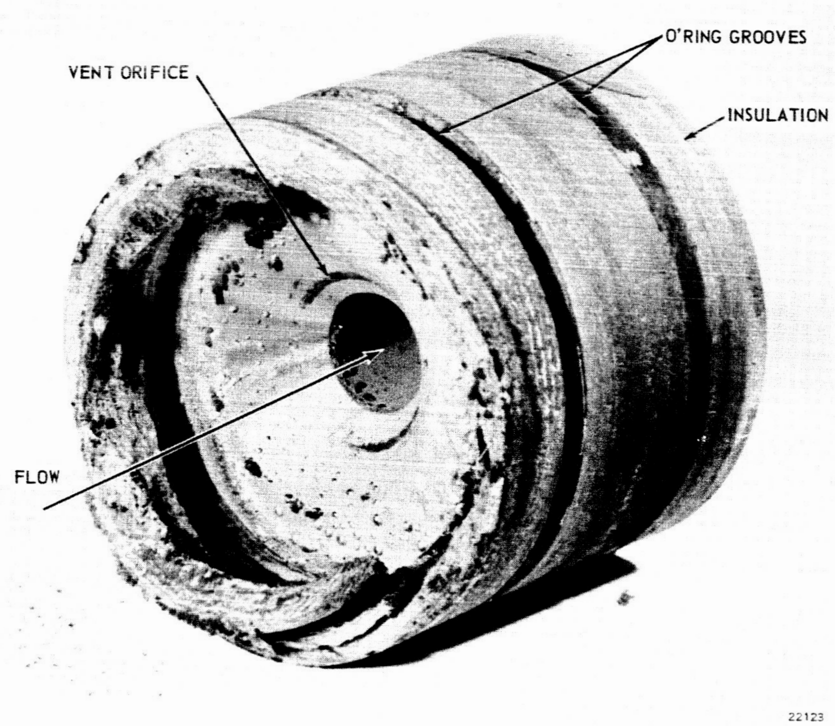


Figure A-34 - Vent Orifice and Insulation (Post Firing)

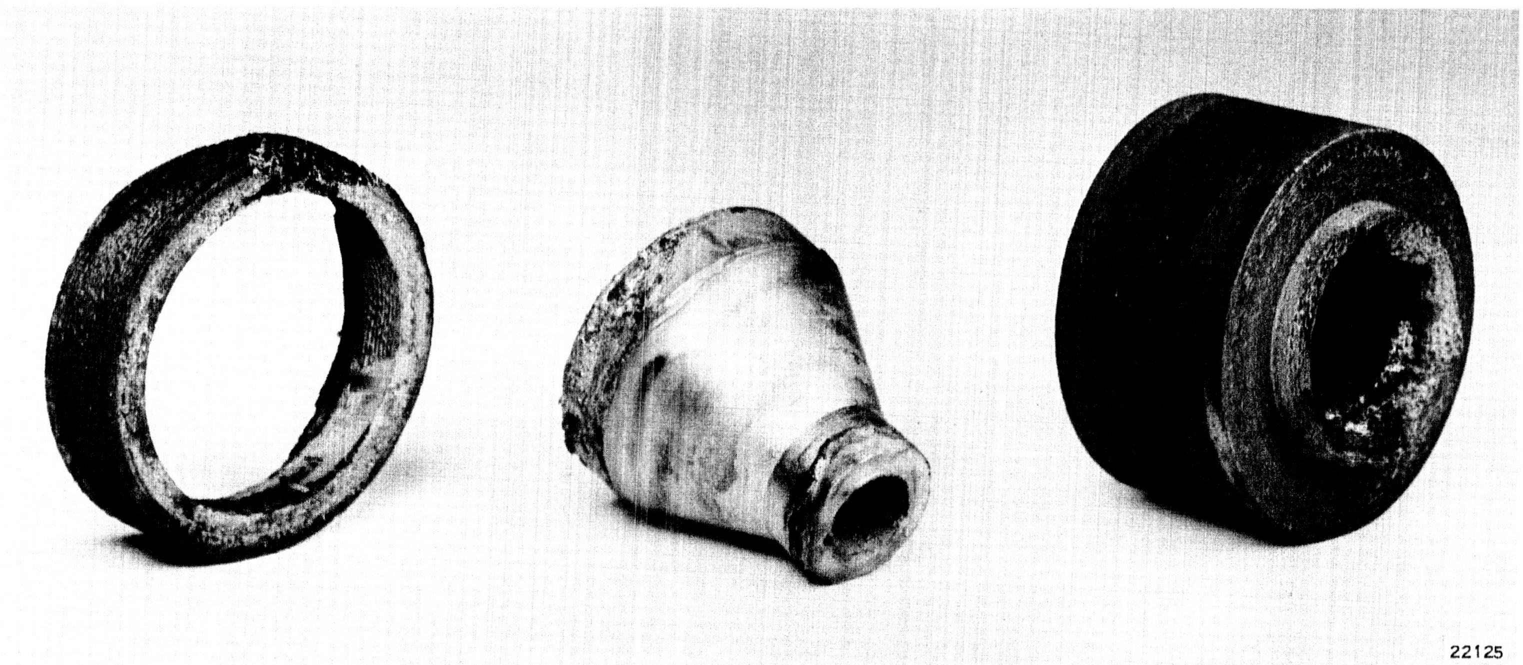


Figure A-35 - Vent Orifice and Insulation (Post Firing)